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FUEL TANK NON-NUCLEAR VULNERABILITY TEST PROGRAM

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Wright-Patterson Air Force Base, Ohio

February 1975

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The effort described herein was designed to obtain weapons' effects data on fuel tanks and their peripheral areas in support of an ASD non-nuclear survivability program. Specifically, the objectives of this program were to obtain data to assist in determining: (1) probabilities of fuel tank explosions, and (2) probabilities of fires in void areas adjacent to fuel tanks, caused by certain non-nuclear combat threats. An additional objective was to evaluate the effectiveness of the level of nitrogen inerting proposed for aircraft fuel tanks. (Continued on reverse side)

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In excess of 550 gunfire tests were performed to establish the probabilities of fire and explosion and to parametrically evaluate the effect of certain variables on these probabilities. The threats utilized in these tests were steel fragments. The major variables tested were the fragment size and velocity, the simulated fuel tank wall and aircraft skin materials, and the fuel vapor concentration in the ullage.

The data obtained from these tests will be especially useful in the performance of vulnerability analyses. The probabilities of explosion and fire used in vulnerability analyses are almost always merely an educated guess made by a cognizant engineer in the absence of any significant amount of related test data. The data obtained in this program provides the engineer with a considerable amount of test data, and also provides some indication of the manner in which this data may be extrapolated to other conditions.

Twenty-six tests were performed to evaluate the effectiveness of the proposed design inerting level (10% oxygen by volume) against threats ranging from fragments through 23 mm high explosive incendiary projectiles. As a result of these inerting tests and an earlier inerting test program, it is concluded that the proposed design inerting level will effectively prevent fuel tank explosions except possibly for a very few and limited situations.

In order to perform the fuel tank explosion tests and the inerting level effectiveness tests in a proper, accurate, and timely manner, it was necessary to use pentane as the fuel. Over 100 tests were then performed in order to allow extrapolation of the results of the pentane tests to JP-4.

FOREWORD

This report was prepared by Mr. A. Ferrenberg with the assistance of Mr. Joel Blickenstaff of Systems Research Laboratories, Inc. (SRL), Dayton, Ohio. The testing described in Sections II, III, and IV of this report was performed by Mr. Blickenstaff under Contract No. F33615-73-D-0473, Task 7546-01, with the Fire Protection Branch of the Air Force Aero Propulsion Laboratory, and under the direction of Mr. Ferrenberg. The testing described in Section V was performed by Mr. Ferrenberg in the facilities of the Fire Protection Branch.

The AFAPL/SFH financial and manpower support was provided under Project 3048, "Fuels, Lubricants and Fire Protection," Task 304807, "Aerospace Vehicle Fire Protection," Work Unit 30480756, "Characterization of Fire Properties and Survivability/Vulnerability Protection." The efforts described in this report were performed during the period of February 1973 to February 1974.

The authors gratefully acknowledge the assistance of Messrs. R. Brislawn and J. Rievley (ASD/ENYX), D. Voyls (AFFDL/PTS), J. Wallick (ASD/ENYS), and R. Clodfelter (AFAPL/SFH) for assistance in planning and managing this program; Mr. L. Gilbert, Capt. J. Grohowski, Capt. K. Tallman, Messrs. R. Studebaker, T. Seymour, W. Gaines, and P. Gollnitz of the AFFDL Ballistic Impact Test Facility for gunrange support; Messrs. F. Deutscher (SRL), P. Hansford (SRL), W. Hall (AFAPL/TFT), and D. Foster (AFAPL/TFT) for assistance in the performance of the tests; and Messrs. J. McCoy and R. Butler of the Fuels Branch of the AFAPL for analysis of the fuel and other technical support and advice.

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INTRODUCTION

AIRCRAFT FUEL FIRES AND FUEL TANK EXPLOSIONS

Two of the primary causes of aircraft losses in combat environments are: (1) fuel fires in empty compartments or spaces (void areas) adjacent to fuel tanks, and (2) fuel tank explosions. Void area fires are caused by projectiles or fragments passing through the aircraft skin, the void space, and the fuel tank wall into the liquid fuel, thereby causing fuel leakage into the void space. In passing through the aircraft skin and fuel tank wall, an incendiary projectile will often produce an incendiary flash or fireball, and a fragment will produce an impact flash. The fuel pouring into the void area may then be ignited by the flash or fireball, causing a void area fire. When the projectile or fragment enters the ullage space of the fuel tank (space above the fuel surface), it can ignite the fuel vapors in the ullage. The resulting rapid combustion of these vapors will usually produce sufficient pressure to rupture or explode the fuel tank. The probability of a fuel tank void area fire or a fuel tank explosion is highly dependent upon many different variables, such as type of threat, fuel tank and aircraft skin materials and thicknesses, angle of obliquity, threat (projectile) velocity, altitude, temperature, and the conditions of the liquid fuel and ullage at the time of impact. The effect that most of these variables have on the probability of a void area fire or fuel tank explosion is not well known. A portion of the program described herein was an attempt to better define the effects of some of these variables in general and, specifically, to estimate probabilities of fires (P_f) and probabilities of explosions (P_e) under conditions representative of an actual aircraft.

The primary application of this P_e and P_f data will be in the analytical determination of the vulnerability of aircraft to nonnuclear threats. This process involves a very extensive and complicated procedure known as a vulnerability analysis.

The vulnerability analysis determines the vulnerable area of the aircraft for a defined "kill category," given a hit by the threat of concern. Analytically, this concept can be expressed as:

$$A_V = \sum_{i=1}^{n} A_{V_i} = \sum_{i=1}^{n} P_{K/D_i}\, P_{D_i/H}\, A_{P_i}$$

where

A_V ≡ Vulnerable area of the aircraft.

A_{V_i} ≡ Vulnerable area of a critical component.

n ≡ The number of critical components, damage of which would cause an aircraft "kill."

P_{K/D_i} ≡ Probability of aircraft "kill," given a level of damage sustained by the critical component.

$P_{D_i/H}$ ≡ Probability of a level of damage caused by the threat of concern, given that it hits the critical component.

A_{P_i} ≡ The presented area of the critical component.

Obviously, the fuel tanks' presented area is a very large portion of the total aircraft's presented area. Neglecting the damage caused by fuel leakage with no fire, the probability of causing severe damage to the fuel tanks ($P_{D_i/H}$) is the probability that an explosion or fuel fire will occur when a projectile pierces the fuel tank wall. Therefore, in order to obtain a reasonably accurate assessment of the vulnerability of an aircraft, it is imperative that a reasonably accurate value be assigned to the probability of a fuel tank explosion or fire. Unfortunately, there is very little data available to establish, or even estimate, probabilities of fuel tank explosions and fires. This is especially true when all the variations in the large number of parameters that affect P_f and P_e are considered. Therefore, when the engineers performing a vulnerability analysis reach the point where values for P_f and P_e are required, they must choose values based upon the limited data available. Also, in some cases single values are chosen for P_f and P_e, and these are applied for all the different aircraft fuel tank configurations and structures, for all the threat velocities and obliquities, and for all the different fuel tank conditions. This is very unrealistic and can lead to considerable error in assessing the vulnerability of an aircraft. Therefore, extensive and accurate data is required in order to realistically and accurately predict P_f and P_e for the great variations in the large number of influencing variables, and these probabilities should be allowed to vary with these influencing variables in the performance of a vulnerability analysis.

DETERMINATION OF PROBABILITIES OF FIRES AND EXPLOSIONS

In order to partially satisfy this requirement for data, series of tests were performed to determine P_f and P_e under a number of conditions representative of operational aircraft. It is, of course, impractical to simulate all the potential conditions, threat variables, structural materials, and material thicknesses that might occur, due to the very large number of tests that would be required. Also, due to the inherent randomness or nonrepeatability of certain parameters, it is necessary to perform and interpret the results of tests involving gunfire in a statistical manner. Examples of some of these parameters are:

- Tumbling of the projectile.
- Interactions between the projectile and the materials through which it passes.
- Interactions between the fragment and the liquid fuel.
- The impact flash size, shape, intensity and duration.
- The liquid fuel spray pattern caused by the projectile entering the liquid fuel.
- The interaction of the liquid fuel spray or the fuel vapors with the projectile impact flash.

The effect of these parameters is considered random for any set of specified test conditions, thereby requiring a statistical approach to the program. A statistical approach necessarily requires a large number of data points at each test condition, thereby further increasing the number of tests required.

Since a large number of tests were required to completely evaluate each parameter that could affect fuel fires and expolsions, not all of these parameters could be completely evaluated. The primary variables that were evaluated were the projectile velocity and fuel tank ullage fuel/air ratio. Other series of tests were performed to provide a less complete evaluation of the effects of such variables as fuel tank and aircraft skin materials, material thickness, and the size, shape, and mass of the fragment. Some potentially important parameters that were not tested as a part of this program were the angle of obliquity, altitude, airflow, incendiary and contact detonating high explosive rounds, nonhomogeneous fuel/air mixtures in the ullage, void area size, and bladder fuel cells. Limited information is available concerning the effects of some of these variables. This information will be utilized where applicable to provide an estimate of the effects of some of these untested variables on the probability of a fire and explosion.

TYPES OF TESTS TO DETERMINE P_f AND P_e

The portion of the test program that had the objective of obtaining data to be used in the determination of approximate values of P_f and P_e is divided into two sets of tests, primarily by type of test. These two types of tests are void area tests and uninerted ullage tests. A third type of test, referred to as inerted ullage tests and consisting of an evaluation of the effectiveness of the 10% oxygen fuel tank inerting level, will be discussed later. The void area and uninerted ullage tests will be briefly discussed now, and the details and results of these tests will be presented in Sections II and III of this report.

The objective of the void area tests was to determine the effect of fragment velocity on the probability of a fire in three configurations representative of an actual aircraft. The only variables in these tests were the target configuration and the velocity of the fragment. The configurations tested were:

1. A simulated dry bay or void area between an aluminum aircraft skin and an aluminum tank wall.

2. A simulated dry bay or void area between a titanium skin and an aluminum tank wall.
3. An integral fuel tank (fuel adjacent to aircraft skin, i.e., no void area) constructed of titanium.

The primary objective of the uninerted ullage tests was to determine the effect of a number of different variables on the probability of an explosion in the fuel tank ullage. These variables are:

1. Tank wall material
2. Fragment velocity
3. Fragment size
4. Fuel/air ratio

Each of the above test parameters was independently varied. Also, a few additional uninerted ullage tests were performed to rudimentarily evaluate the effects of titanium tank wall thickness, painted entrance plates, and fragment shape. In order to accomplish the large number of uninerted ullage tests that were required, and in order to adequately control fuel/air ratio, normal pentane was used as the fuel in all of these uninerted ullage tests. A series of tests to compare and correlate the combustion of pentane vapors with the combustion of JP-4 vapors was also performed and is described in Section V.

SIMULATION OF FRAGMENT THREATS

The fragments utilized in these tests were the hexagonal fragments having a mass of either 180 grains or 90 grains (see Figure 1). They were fabricated from 8620 hot rolled steel. The weights of these fragments and the type and hardness of the steel are as close as possible to the average of those properties of the fragments produced by certain foreign missile warheads. Fragments of the same weight and similar materials, but of a diamond shape, were used in other test programs which were related to aircraft vulnerability. The diamond shaped fragments shown in the figure simulate the approximate, and apparently intended, shape of the fragments produced by the missiles. The hexagonal shaped fragment was used in lieu of the more realistic diamond shaped fragment because the hexagonal

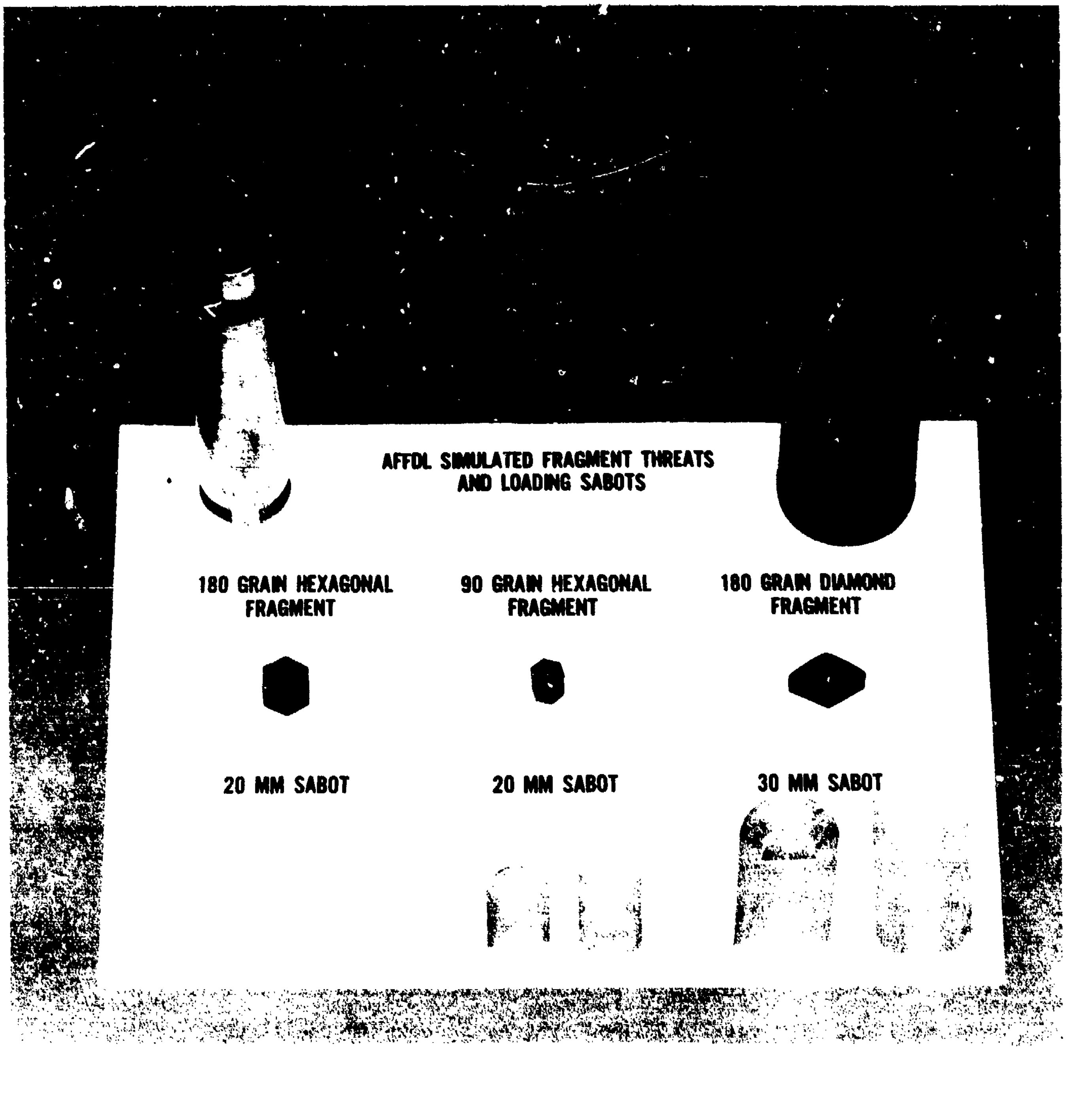


FIGURE 1. FRAGMENT THREATS AND SABOTS

fragment could be more easily fabricated and launched from an available weapon. Thirty uninerted ullage tests were performed with the diamond shaped fragment in order to provide a comparison of the effects of the shape of the fragment on the probability of a fuel tank explosion. No void area tests were performed with the diamond shaped fragment.

The fragments were mounted in Lexan sabots which separated into two pieces immediately after launching. In many tests one of the pieces of the sabot would impact the test tank and even the target plates. In a few of the uninerted ullage tests, a sabot piece actually passed through the entrance plate and into the test tank, thereby invalidating those tests. It was pointed out by other test personnel that the sabots could produce a sizable impact flash and thereby invalidate some of the void area tests. A sabot trap (a metal plate with a small hole) was subsequently installed about midway through the uninerted ullage test phase. High speed motion pictures were taken of all the void area tests, and no evidence of any flashes produced by the impacts of the sabots was observed on the films. Most of the void area tests were performed at relatively low projectile velocities (1500 to 2500 ft/sec), and this may in part account for the absence of sabot impact flashes. Also, due to the shape and mass of these sabot pieces, their velocities may have been considerably reduced due to air resistance encountered during their flight.

SIMULATION OF AIRCRAFT SKIN AND FUEL TANK WALL MATERIALS

The entrance plate (simulated tank wall) and the striker plate (simulated aircraft skin), which was used only in void area tests, were varied in these tests. These plates were either a 0.060 in. 6Al-4V titanium sheet or a 0.090 in. 2024-T3 aluminum sheet. Type 6Al-4V titanium, in various thicknesses, will be a significant portion of the material used on future aircraft. Initially, it was planned that this titanium material would be used almost exclusively in this test program, even though a much greater portion of aircraft are of aluminum construction. It was planned in this manner in order to keep the number of shots required to a minimum and to provide a worst case test material, from the viewpoint of the impact flash. However, after the program had begun it was decided that testing of aluminum plates would also be performed.

The thicknesses of aircraft skin and fuel tank wall materials vary over a wide range. The 0.060 inch titanium was chosen to be somewhat representative, and the 0.090 inch aluminum was used due to rapid availability. The effect of material thickness was evaluated, to a very limited extent, as a portion of the uninerted ullage tests. No attempt was made to simulate the structural members of the aircraft to which the aircraft skin and fuel tank walls are attached.

The effect that paint, on the aircraft skin or fuel tank wall, could have on the probabilities of a fire or explosion was initially assumed to be negligible. However, very late in this test program, an unrelated program being performed at Wright-Patterson AFB obtained some preliminary test data regarding impact flashes that indicated the effect of the paint might be considerable. Ten additional uninerted ullage tests were then performed to provide an estimate of the importance of this factor. Although these tests did not show any difference between painted and unpainted target plates, the number of tests performed were too few to completely eliminate or disregard the significance of this test variable.

FUEL TANK NITROGEN INERTING

Fuel tank nitrogen inerting is a state-of-the-art technique for the prevention of explosions in aircraft fuel tanks. The technique involves diluting with nitrogen a portion of the air that normally enters a fuel tank during a descent or as the fuel is withdrawn. In this manner the oxygen content of the nitrogen enriched air mixture in the fuel tank ullage is maintained at a level which will not support combustion. The required nitrogen is normally stored onboard the aircraft as a cryogenic liquid in a dewar. The volume and weight of this dewar and the liquid nitrogen that must be carried depend upon the capacity of the aircraft's fuel tanks, the type of mission anticipated, the aircraft's vent system, the number of flights desired before replenishment of the liquid nitrogen is required, and the effect of this additional weight and volume on the aircraft's range, payload, and performance. In an effort to reduce this volume and weight penalty, several techniques for the onboard generation of inert gas are being investigated and/or developed.

In order to minimize the quantity of liquid nitrogen required, nitrogen inerting systems are usually designed to allow a maximum oxygen concentration that is just slightly below the level which will support combustion. In other words, the safety factor is reduced. However, since this maximum allowable oxygen concentration will normally occur for only a few short periods during a given mission, this reduction in safety factor is justified. The maximum allowable oxygen concentration is often considered to be 10% oxygen by volume. Normally, the oxygen concentration will be considerably less than the 10% level.

It is evident from the preceding discussion that the maximum oxygen concentration which will not support combustion (maximum "safe" oxygen concentration) is an important parameter to consider in the design of a nitrogen inerting system. Although considerable testing to determine the maximum "safe" oxygen concentration has been done, the published results vary from 9.5% to 12% oxygen by volume. Also, much of this data has been obtained under test conditions that do not allow a reasonable extrapolation of the test data to aircraft fuel tanks. Finally, it has been assumed by many engineers that a unique, single, and universal, maximum "safe" oxygen concentration exists. Although a unique and single oxygen concentration, below which a particular hydrocarbon flame cannot propagate, does exist for a specific set of conditions, this does not imply that an oxygen concentration below this level is safe under all conditions. This is explained in Reference 1 and will be discussed in detail in Section IV.

INERTED ULLAGE TESTING

The objective of the inerted ullage testing was to evaluate the effectiveness of the proposed inerting level (maximum 10% oxygen by volume) under conditions representative of larger aircraft. All of these tests were performed in pentane/air/nitrogen mixtures in which the oxygen concentration was maintained at 10% by volume. The threats utilized in these tests ranged from the 90 grain hexagonal fragment to a 23 mm high explosive incendiary round. This data, along with data obtained in a previous test program,[1] provide the basis for the assessment of the effectiveness of the 10% oxygen concentration in preventing significant combustion overpressures in aircraft fuel tanks.

Section II
VOID AREA TESTS

VOID AREA FIRES

Void areas or dry bays are spaces on an aircraft that are adjacent to a fuel tank. These may include such areas as weapon bays, spaces for control cables and instrumentation and power lines, cargo areas, electronics bays, crew compartments, and any space between an aircraft's skin and the fuel tank wall. When a projectile or fragment passes through the aircraft's skin and any other intervening structures or surfaces and into the fuel tank below the level of the liquid fuel, a potential for a fuel fire exists. The impact of a fragment on the aircraft skin and fuel tank wall produces a flash and a number of hot, incandescent particles or sparks. The size, shape, intensity, and duration of the flash and sparks depend upon the size, shape, mass, and velocity of the fragment, the angle of obliquity (angle between the fragment's path and a normal to the impacted surface), the material type and thickness of the impacted plate, and the geometry of the void area. The impact flash is usually attributed to a rapid oxidation (combustion) of very fine particles or vapors of the impacted material. The incandescent particles or sparks are small pieces of the impacted material or fragment which are heated to very high temperatures by the impact and may also be reacting with the available air. If the fine particles and vapors are undergoing some oxidation, it would seem reasonable to expect that a decrease in the oxygen concentration or a decrease in the partial pressure of oxygen (due to increasing altitude) would result in a decrease in the intensity of the impact flash. This has been observed,(2) although it must be noted that the flash is not entirely eliminated when the oxygen is completely replaced by an inert gas, and the effect of lowering pressures is small up to altitudes of about 60,000 ft.

The impact flash usually occurs on both sides of the penetrated sheet or plate. The relative sizes and intensities of the flashes on the front and back sides of the sheet or plate depend upon the plate thickness, angle of obliquity, and fragment velocity, for a given plate material and fragment. For the void area tests described in this report, the impact flash on the back side of the impacted materials was much greater than that which occurred on the front side.

When the projectile or fragment penetrates the fuel tank wall and enters the liquid fuel, it creates large and very transient hydraulic ram forces within the fuel tank. These forces are at least partly responsible for the initial spurt of fuel out of the projectile hole in the fuel tank wall. This initial spurt provides the fuel that is ignited by the impact flash or hot particles. The fuel fire occurs when the fuel spurt contacts the impact flash and/or hot incandescent particles. The initial fuel spurt is usually in the form of a fine spray or mist, and burns very rapidly after ignition. The rapid combustion of this initial fuel spurt can result in significant and damaging overpressures within void areas.[3,4] The occurrence of a void area fire is dependent upon all the previously mentioned factors influencing the impact flash, as well as all factors which influence the initial fuel spurt size, velocity, and droplet size distribution. Since the fuel droplets must evaporate to some extent before ignition can occur, it might be expected that the ambient air temperature and liquid fuel temperature are factors influencing P_f. A slight positive correlation of P_f with both increasing fuel temperature and increasing ambient temperature has been noted in previous AFAPL gunfire test programs. All data related to the effect of pressure on the ignitability of fuels indicates that the probability of ignition should decrease with increasing altitude. However, the degree to which this occurs is unknown, and fuel fires can occur at altitudes as great as 70,000 ft.

The absence of a void area generally appears to enhance the survivability of an aircraft. If the fuel tank wall is the aircraft skin (integral fuel tank), then P_f may be considerably lower than when a void area is present. This is due to the fact that the external airflow can sweep away the impact flash or the fire itself if the aircraft's velocity is in excess of about 100 miles per hour.[4,5] However, this "flame blowoff" may not occur if the damage caused by the impact or if the aircraft structure itself acts as a flameholder and thereby prevents blowoff.

VOID AREA TEST CONDITIONS

The objective of the void area tests was to determine the effect of fragment impact velocity on P_f under conditions representative of an operational aircraft. To simulate these conditions a test article was designed as shown in Figure 2. The striker plate simulates the aircraft skin, and the entrance plate simulates the fuel tank wall. Since it was impossible to accurately simulate and test every possible void ar a configuration to be found on an aircraft, the scope of this test effort was limited to the following three representative test configurations.

- 0.060 in. 6Al-4V titanium striker/0.090 in. 2024-T3 aluminum entrance plates
- 0.090 in. 2024-T3 aluminum striker and entrance plates
- No striker/0.060 in. 6Al-4V titanium entrance plate (no void area)

The first configuration was considered to be the "worst case" configuration and was tested most extensively. An 11 in. spacing between the entrance and striker plates was chosen and maintained throughout these tests. The space between the striker and entrance plates was not enclosed, thereby providing sufficient air to prevent a fire from smothering itself. All tests were performed at zero degree obliquity with the large (180 grain) hexagonal fragment. The test tank used for these tests was a 90 gallon rectangular steel tank with a 7-3/4 in. port for the fragment entrance area. The entrance plate was held in place by a steel ring and bolted against a 9 in. O-ring seal. The rear section of the tank was filled with 4 in. × 4 in. blocks of wood to reduce the amount of fuel required and to stop the projectile. This eliminated the need to replace the plate on the rear section of the test article after each test. A 2 in. valve was used to dump the residual fuel after each test. A test tank having a different shape was used for the aluminum striker/aluminum entrance (Al/Al) tests, but the entrance hole, seals, plate spacing, tank volume, and all other important test tank configuration parameters were the same as those described above.

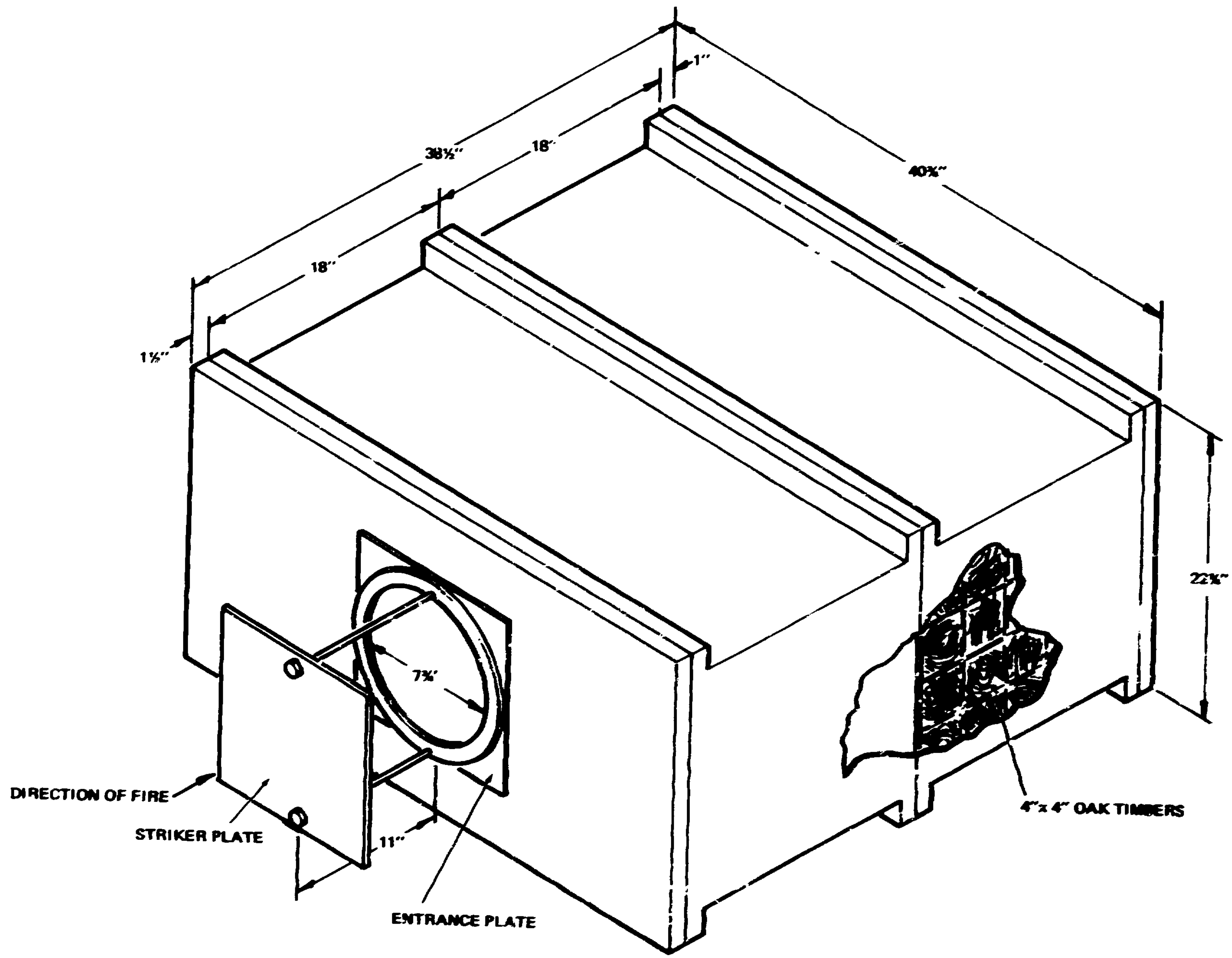


FIGURE 2. VOID AREA FIRE TEST SETUP.

The fragment was mounted in a split Lexan sabot and fired from a 20 mm cannon. The fragment's velocity was controlled by varying the amount of powder in the shell and was measured by a velocity screen/chronograph system with an accuracy of ±0.25%.

The fuel used in the void area tests was JP-4. The fuel temperature was normally maintained at 90°F ± 10°F. The fuel level was monitored via a site gage located on the side of the test article. The fuel level was maintained at about seven inches above the center of the entrance plate. This resulted in a large amount of fuel leakage after impact, and when a fire occurred, it rapidly enlarged in size and intensity. A large CO_2 nozzle was located directly above the void space, but was usually ineffective in controlling the fire. Most fires were extinguished by a Wright-Patterson Air Force Base Fire Department truck which was standing by during all tests.

Five hundred frames per second motion picture coverage was obtained for each test except for a few tests where 7,000 frames per second coverage was provided. The only other instrumentation was a thermocouple located in the test tank to determine fuel temperature.

VOID AREA TEST PROCEDURE

The test procedure was as follows:

1. Heat the fuel in 55 gallon drums to the desired temperature.
2. Examine the stacked wood inside the test article to ensure that it adequately protects the rear section of the test article and is at least 18 in. behind the entrance plate.
3. Attach the entrance plate and striker plate.
4. Attach the fuel fill hose to the tank via a quick-disconnect fitting, insert the pump suction hose into a full drum, start the pump and fill to the stated level.
5. Disconnect fill hose.
6. Check CO_2 system.
7. Clear firing area of personnel.
8. Fire weapon.

9. If fire occurs, extinguish flames.

10. Record the following data:

    a. test number

    b. striker and entrance plates used

    c. projectile velocity

    d. fire or no fire

    e. test article fuel temperature

    f. point of fragment impact relative to the original fuel/ullage interface.

VOID AREA TEST DATA AND RESULTS

Table I is a collection of all the test data obtained in the void area tests. In some tests the chronograph system failed and the velocities were unknown. The distance below the ullage is the vertical distance between the point of impact of the fragment and the liquid JP-4 fuel surface. This parameter was subsequently considered to be unimportant and was not measured in the last void area configuration (aluminum striker/aluminum entrance) tested. The data plotted in Figures 3 and 4 is the number of fires and total tests as a function of 250 ft/sec velocity intervals. Figure 3 depicts the results of the titanium striker/aluminum entrance configuration, and Figure 4 depicts the aluminum striker/aluminum entrance configuration results. The tests performed with no striker and a titanium entrance plate (integral fuel tank - no void area) were too few to establish any meaningful correlation of P_f with fragment velocity. However, these tests do indicate that the probability of a fire is considerably lower for the integral fuel tank configuration tested as compared to the other two configurations.

The motion picture coverage of the void area tests was most useful in analyzing these tests. First, the impact flash on the back side of the striker plate was far more intense and larger than the flash on the front side. The duration of this flash was on the order of 2 msec. The titanium striker caused a more intense flash than the aluminum striker. Also, the titanium striker plate impacts generally resulted in larger and more intense sparks or

TABLE I

VOID AREA FRAGMENT TESTS — 180 GR. HEX FRAGMENT — .060 6AL–4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
1	59	4901 FPS	Unknown	No	Single TI Plate (.060 in. 6AL-4V)
2	80	4938 FPS	---	No	Missed Tank "
3	70	4938 FPS	Unknown	No	"
4	78	5586 FPS	8.0	No	"
5	78	5434 FPS	6.0	Yes	"
6	76	3616 FPS	9.0	Yes	"
7	95	4739 FPS	6.75	Yes	"
8	86	5800 FPS	8.25	No	"
9	80	3861 FPS	6.75	No	"
10	88	5747 FPS	7.5	No	"
11	86	5698 FPS	6.5	No	"
12	84	5479 FPS	6.25	Yes	"
13	87	5390 FPS	8.0	No	"
14	96	3115 FPS	6.0	Yes	"
15	101	5208 FPS	9.0	Yes	"
16	103	4938 FPS	9.5	No	"
17	70	4950 FPS	6.0	Yes	.060 in. 6AL-4V TI Striker Plate, .090 in. 2024-T3 AL Entrance Plate, 11 in. Standoff
18	56	4807 FPS	6.0	Yes	"
19	90	3636 FPS	6.0	Yes	"
20	90	4842 FPS	6.0	Yes	"

TABLE I (continued)

VOID AREA FRAGMENT TESTS – 180 GR. HEX FRAGMENT – .060 6AL–4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
21	85	2836 FPS	6.0	Yes	.060 in. 6AL-4V TI Striker Plate, .090 in. 2024-T3 AL Entrance Plate, 11 in. Standoff
22	93	2372 FPS	7.0	Yes	"
23	104	4587 FPS	6.0	Yes	"
24	---	---	---	---	No Test "
25	92	4651 FPS	6.0	Yes	"
26	65	1196 FPS	Unknown	No	"
27	95	Unknown	6.0	No	No Test "
28	80	Unknown	Unknown	Yes	No Test "
29	84	2460 FPS	"	Yes	"
30	94	2285 FPS	"	Yes	"
31	87	2853 FPS	"	Yes	"
32	82	2902 FPS	"	Yes	"
33	88	2906 FPS	"	Yes	"
34	75	4566 FPS	6.0	Yes	"
35	91	4201 FPS	6.0	Yes	"
36	75	1144 FPS	7.5	No	"
37	95	2503 FPS	7.0	Yes	"
38	92	2283 FPS	Unknown	Yes	"
39	95	2597 FPS	7.0	Yes	"
40	60	2604 FPS	6.0	Yes	"

TABLE I (continued)

VOID AREA FRAGMENT TESTS – 180 GR. HEX FRAGMENT – .060 6AL–4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
41	93	2652 FPS	4.0	Yes	.060 in. 6AL-4V TI Striker Plate, .090 in 2024-T3 AL Entrance Plate 11 in. Standoff
42	90	2398 FPS	5.0	Yes	"
43	89	Unknown	5.5	Yes	No Test "
44	80	2415 FPS	5.5	Yes	"
45	94	2472 FPS	5.0	Yes	"
46	98	2635 FPS	5.0	Yes	"
47	90	2628 FPS	4.0	Yes	"
48	100	Unknown	5.0	Yes	No Test "
49	82	2421 FPS	4.0	Yes	"
50	72	2244 FPS	4.0	No	"
51	100	2188 FPS	5.0	Yes	"
52	106	2166 FPS	6.0	Yes	"
53	106	Unknown	4.0	No	No Test "
54	102	2092 FPS	5.25	No	"
55	108	1915 FPS	4.0	Yes	"
56	105	1579 FPS	3.0	No	"
57	92	Unknown	4.25	No	No Test "
58	90	Unknown	3.5	No	No Test "
59	95	1740 FPS	5.13	No	"
60	99	1824 FPS	5.5	No	"

TABLE I (continued)

VOID AREA FRAGMENT TESTS – 180 GR. HEX FRAGMENT – .060 6AL–4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
61	94	1668 FPS	4.0	No	.060 in. 6AL-4V TI Striker Plate, .090 in. 2024-T3 AL Entrance Plate, 11 in. Standoff
62	97	1883 FPS	5.0	No	"
63	86	1659 FPS	6.0	No	"
64	98	1610 FPS	6.0	No	"
65	106	2717 FPS	Unknown	Yes	"
66	86	1706 FPS	7.0	No	"
67	82	2283 FPS	6.0	Yes	"
68	87	2652 FPS	6.0	Yes	"
69	90	1890 FPS	6.0	No	"
70	92	1966 FPS	8.0	Yes	"
71	92	1573 FPS	6.0	No	"
72	95	1955 FPS	5.0	No	"
73	93	2047 FPS	4.0	No	"
74	87	2293 FPS	6.0	Yes	"
75	85	2207 FPS	7.0	Yes	"
76	90	2259 FPS	5.5	Yes	"
77	100	2004 FPS	Unknown	No	"
78	90	2222 FPS	Unknown	Yes	"
79	85	Unknown	5.0	Yes	No Test "
80	95	Unknown	5.5	No	No Test "

TABLE I (continued)

VOID AREA FRAGMENT TESTS – 180 GR. HEX FRAGMENT – .060 6AL–4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
81	100	2143 FPS	3.0	Yes	.060 in. 6AL-4V TI Striker Plate, .090 in. 2024-T3 AL Entrance Plate, 11 in. Standoff
82	95	1818 FPS	6.0	No	"
83	92	1955 FPS	6.5	No	"
84	95	5617 FPS	6.0	Yes	"
85	80	2079 FPS	7.0	Yes	"
86	85	Unknown	5.5	Yes	No Test "
87	86	Unknown	6.25	No	No Test "
88	90	1609 FPS	6.75	No	"
89	80	1471 FPS	6.68	No	"
90	95	2057 FPS	4.5	No	"
91	95	772 FPS	5.5	No	"
92	100	2406 FPS	6.0	Yes	"
93	90	2087 FPS	6.0	Yes	"
94	75	1707 FPS	6.0	No	"
95	90	1883 FPS	6.0	No	"
96	100	1579 FPS	6.0	No	"
97	80	2120 FPS	6.0	Yes	"
98	82	1689 FPS	6.0	Yes	"
99	88	1883 FPS	6.5	No	"
100	90	2375 FPS	6.0	Yes	"

TABLE I (continued)

VOID AREA FRAGMENT TESTS — 180 GR. HEX FRAGMENT — .060 6AL—4V TITANIUM STRIKER					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
101	81	1696 FPS	6.0	No	0.060 in. 6AL-4V TI Striker Plate, 0.090 in. 2024-T3 AL Entrance Plate, 11 in. Standoff
102	Not Recorded	2994 FPS	Not Recorded	Yes	0.090 in. 2024-T3 AL Entrance Plate No Test 0.090 in. 2024-T3 AL Striker Plate
103	"	Unknown	"	Yes	No Test "

TABLE I (continued)

VOID AREA FRAGMENT TESTS – 180 GR. HEX FRAGMENT – .090 2024-T3 ALUMINUM STRIKER AND ENTRANCE PLATES					
TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
124	85	1869 FPS	Not Recorded	No	
125	80	Unknown	"	Yes	
126	90	1962 FPS	"	Yes	
127	96	1955 FPS	"	Yes	
128	85	1705 FPS	"	No	
129	93	1479 FPS	"	No	
130	96	1628 FPS	"	No	
131	97	1702 FPS	"	No	
132	96	1712 FPS	"	Yes	
133	94	1654 FPS	"	Yes	

(continued)

VOID AREA FRAGMENT TESTS – 180 GR. [illegible]EX [illegible]AGMENT – .090 2024-T3 ALUMINUM STRIKER AND ENTRANCE PLATES

TEST - NO.	FUEL TEMP.	FRAG. VEL.	DIST. BELOW ULLAGE (IN.)	FIRE	REMARKS
104	Not Recorded	2994 FPS	Not Recorded	Yes	
105	"	Unknown	"	Yes	No Test
106	"	2894 FPS	"	Yes	
107	"	2994 FPS	"	Yes	
108	"	2252 FPS	"	Yes	
109	"	2195 FPS	"	No	
110	"	2244 FPS	"	Yes	
111	"	2254 FPS	"	Yes	
112	"	2234 FPS	"	No	
113	"	2262 FPS	"	Yes	
114	"	1998 FPS	"	No	
115	"	2136 FPS	"	Yes	
116	"	2169 FPS	"	No	
117	"	2155 FPS	"	Yes	
118	"	2038 FPS	"	Yes	
119	"	2139 FPS	"	Yes	
120	"	1765 FPS	"	No	
121	"	1885 FPS	"	Yes	
122	"	2853 FPS	"	Yes	
123	"	2014 FPS	"	Yes	

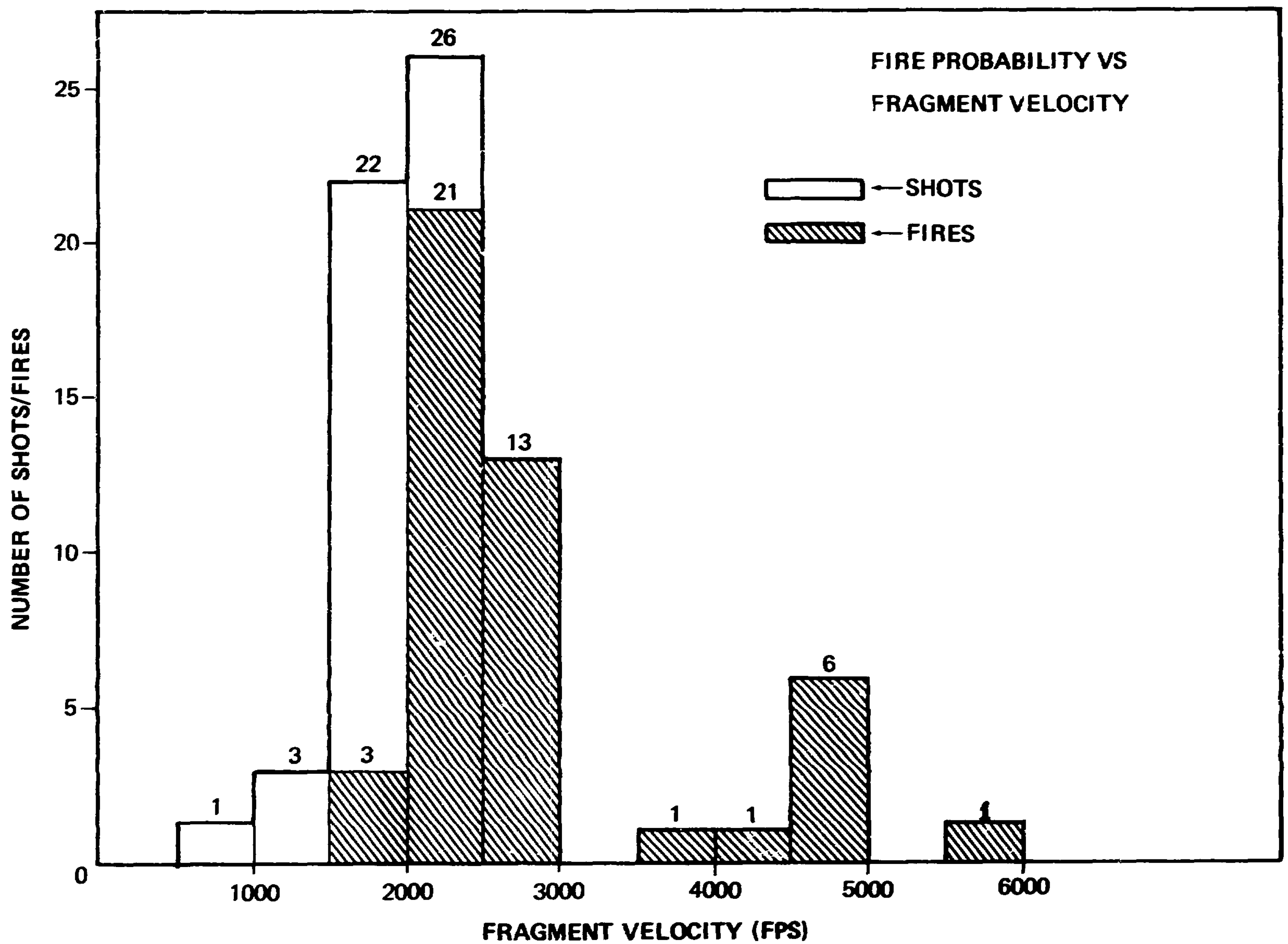


FIGURE 3. VOID AREA TEST RESULTS FOR TITANIUM STRIKER AND ALUMINUM ENTRANCE PLATE.

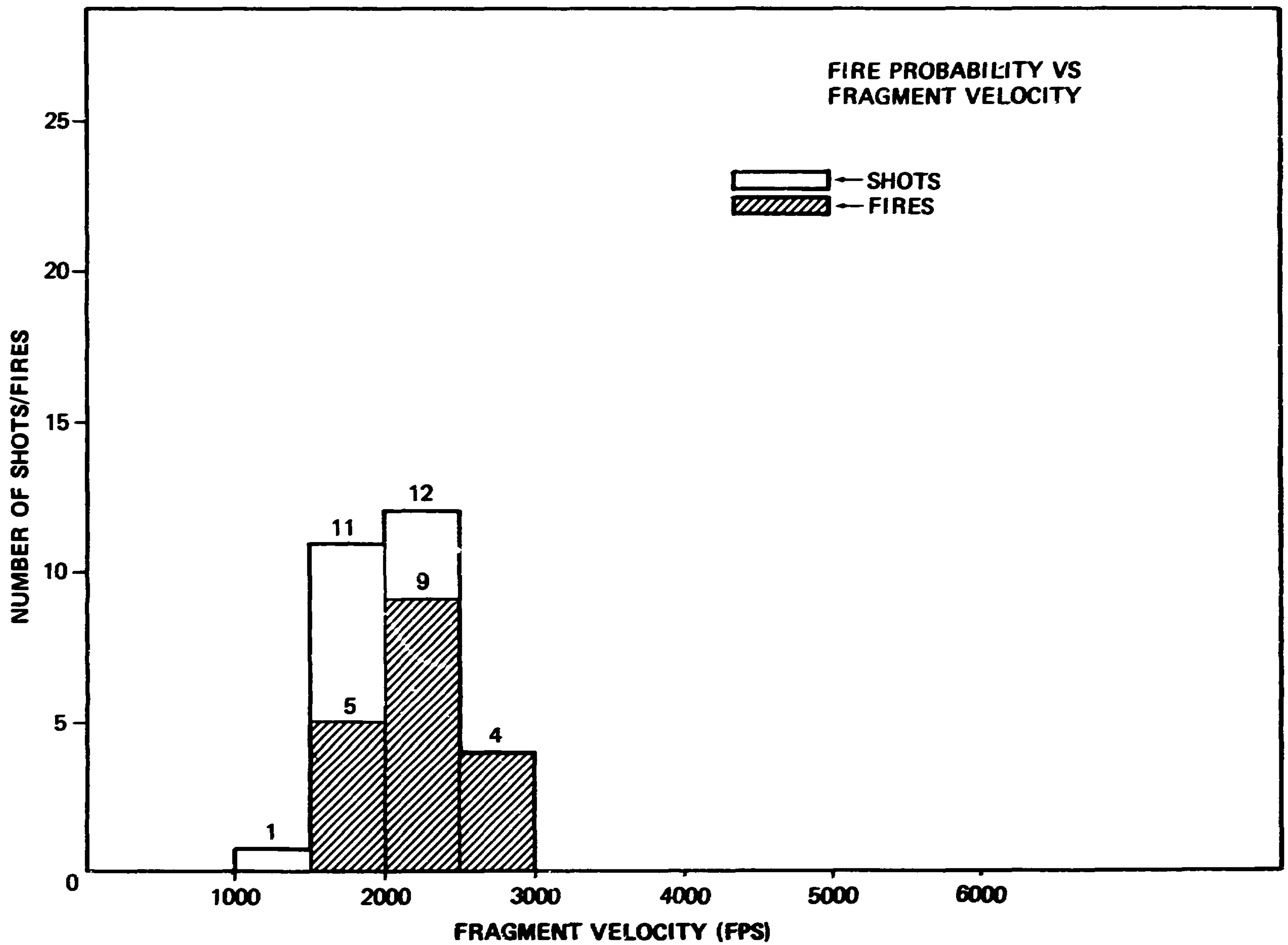


FIGURE 4. VOID AREA TEST RESULTS FOR ALUMINUM STRIKER AND ENTRANCE PLATE.

incandescent particles which appeared to glow for a longer time. The visible lifetime of these sparks was greater than 25 msec for the titanium striker and only about 5 msec for the aluminum striker. Although both the titanium and the aluminum striker plate impacts generated sparks on the front side of the striker plate, these sparks generated on the front side were far fewer in number and appeared to play no role as ignition sources in either of the two void area configurations tested. The sparks generated in the void area appeared to be the result of the striker plate impact, rather than the entrance plate impact. Almost immediately after impact, a fine fuel mist rapidly enters the void area. In most tests the fire appears to be initiated by a small and almost immediate reaction of this fine mist with the impact flash. This reaction lingers in the void area for sufficient time to ignite the spurts of liquid fuel which are propelled from the entrance plate hole with considerable force about 40 msec after impact. Although the point of impact was only about three feet above the ground, these initial spurts of liquid fuel often travelled up to 12 feet away from the test tank before falling to the ground. After these first few spurts of fuel, the fuel would merely pour out of the impact hole. By this time the fire was already established and the additional fuel merely "fed" the fire and did not affect the probability of a fire.

Generally, it appeared as though the entrance plate impact flash was the ignition source. However, in some tests resulting in fires, the impact flash was dissipated before any flames appeared. In these cases the incandescent particles appeared to be the ignition source. This was never observed in the aluminum striker/aluminum entrance configuration. For these aluminum/aluminum configuration tests, the impact flash always appeared to be the ignition source, while in the titanium/aluminum configuration the ignition source was either the impact flash or the incandescent particles. In most of the tests which did not result in a fire, the impact flash was small and fewer sparks were generated and/or the sparks were not in the vicinity of the fine fuel mist. This occurred mainly with the lower velocity shots. Also, the fine fuel mist appeared to be smaller when the fragment's velocity was low.

The exposed area of the entrance plate consisted of a circle of approximately eight inches in diameter. The rest of the plate was covered with the steel retainer ring which held the entrance plate in place. It was suggested that this steel ring might affect P_f, since the steel material was unrealistic and the incandescent particles could be reheated and/or provide additional impact flashes by striking this ring. Based upon analysis of the film data, it was concluded that the effect of the incandescent particles striking the steel ring was minimal at best. When the incandescent particles did strike the retainer ring, they usually had such a trajectory that they bounced away from the void area and the fine fuel mist. Although it was observed that some fires were initiated by incandescent titanium particles bouncing off the entrance plate, no fires were observed to be initiated by particles bouncing off the ring. However, it must be pointed out that in most tests it was not possible to conclusively determine the source of the ignition. Therefore, the effect of the steel ring on the test results cannot be completely proven to be insignificant or nonexistent. It is recommended that any similar test programs be performed with a retainer ring of the same material as the entrance plate.

The fragments did not appear to tumble to any great degree in these void area tests. The penetration of the striker plate usually produced a roughly hexagonal shaped hole and a hexagonal plug of the striker plate material. In some tests the plug would become fused to the fragment. In other tests with a titanium striker plate, the titanium plug would separate from the fragment and both pieces would penetrate the aluminum entrance plate. At velocities in excess of about 4,000 ft/sec, the aluminum entrance plate would rupture, resulting in a very large hole and very severe fires. This may be due to the hydraulic ram forces which are much greater at higher fragment velocities. The few tests performed with no striker plate and a titanium entrance plate did not demonstrate any severe hydraulic ram entrance plate damage, even at velocities in excess of 5,000 ft/sec. This may be due to the greater strength of the titanium.

CONCLUSIONS REGARDING PROBABILITIES OF VOID AREA FIRES

The bar graphs shown in Figures 3 and 4 do not demonstrate any statistically significant difference between the titanium striker and an aluminum striker plate tested. The data from these two types of void area tests are plotted in Figure 5, showing P_f as a function of fragment velocity.

When utilizing this data, it must be kept in mind that these tests were performed under a specific set of test conditions and only the projectile velocity and the test configuration were varied. Furthermore, only two configu-ations were extensively tested. It will often be necessary to extrapolate this test data to other conditions. This must be done very carefully, keeping in mind all the potential and untested variations of the many variables that can affect P_f. These variables will now be discussed and some estimates of the effect they may have on the values of P_f presented in this report will be made whenever possible.

Void Area Depth

The space between the aircraft skin and the fuel tank wall can affect P_f. The impact flash and the sparks generated on the rear side of the striker plate appeared to be the ignition source in these void area tests. If the void area depth was sufficiently large to prevent the impact flash from coming in contact with the fuel mist, and to decrease the density of the sparks, it would seem reasonable to expect a decrease in P_f. Other investigators observed this for the case of an incendiary projectile, but the results cannot be extrapolated to fragment threats. A decrease in P_f with increasing void area depth assumes that the impact flash on the front face of the fuel tank wall is too small to consistently provide a sizable ignition source. This assumption appears valid for the materials and configurations tested in this program. In the tests performed with no striker and the 0.060 in. titanium entrance plate, the impact flashes were able to ignite the fuel mist in only three tests out of the eight tests performed at velocities in excess of 5,000 ft/sec. Thicker fuel tank wall materials and/or greater angles of obliquity would probably serve to increase the impact flash on the front side of the fuel tank wall, thereby preventing a decrease in P_f with void area depth.

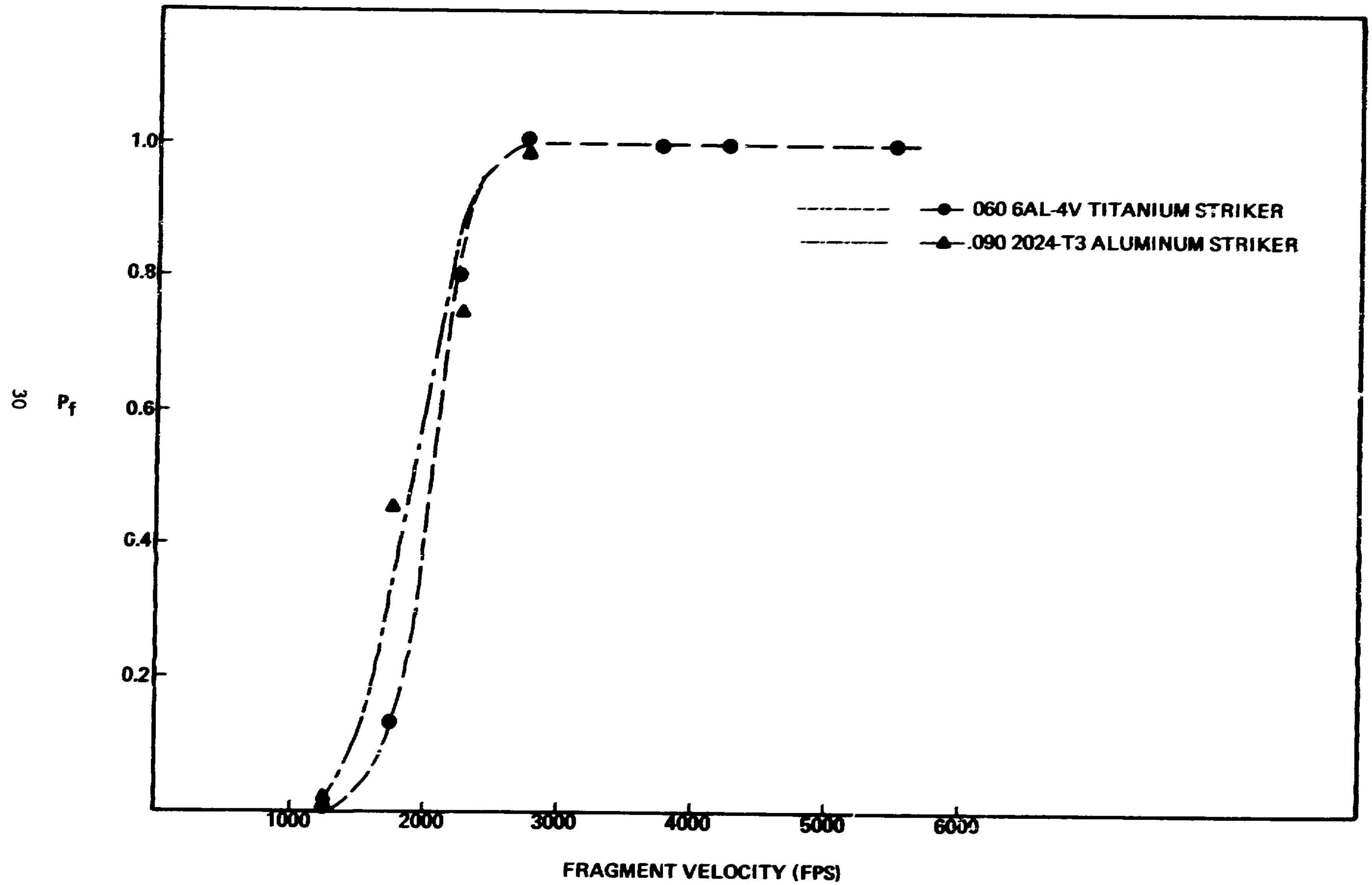


FIGURE 5. VOID AREA TEST DATA P_f VS PROJECTILE VELOCITY 180 GRAIN HEXAGONAL FRAGMENT.

Based upon the above discussion, it would seem reasonable to conclude that P_f should increase from the values obtained in this program as the void area depth decreases. A recently completed AFAPL test program has shown that for a 208 grain cylindrical fragment at approximately 4,800 ft/sec and a 2 in. void area between two 0.090 in. 2024-T3 aluminum sheets, the probability of initiation of a void area fire is nearly one.[10] Recent gunfire testing at the Flight Dynamics Laboratory at Wright-Patterson AFB has also demonstrated that fragments can initiate fires in 2 in. deep void spaces.

If no void area exists, that is, if the fuel tank wall and the aircraft skin are one and the same (integral fuel tank), then the probability of a sustained fuel fire is considerably lower. As was previously mentioned, integral fuel tanks are generally considered to be relatively invulnerable because the impact flash and/or the fuel fire can be "blown off" or swept away by the airstream if the aircraft's velocity is sufficient. The first 16 void area tests performed in this program also indicate that P_f is much lower when no void area exists, even if airflow is not present. The probability that the leaking fuel will be ignited by other ignition sources must be assessed separately.

Materials of Construction

The type of material used for the aircraft skin and the fuel tank wall can affect the impact flash and thereby affect P_f. The results of these void area tests do not indicate any significant difference between a 0.090 in. 2024-T3 aluminum striker and a 0.060 in. 6Al-4V titanium striker with regard to P_f. However, different thicknesses of these materials might have produced different results. Also, as was described in the previous section, the impact flashes and incandescent particles produced on the back sides of these aluminum and titanium striker plates did appear different. Therefore, it cannot be concluded that the material type has no effect on P_f. Another earlier test program has shown that the impact flash on an aluminum plate is larger and more persistent than the flash on a steel plate. The results of the ullage tests described in Section III demonstrate that the probability of igniting vapor/air mixtures is greater for the 0.060 in. titanium than for the 0.090 in. aluminum. Based upon the above information, P_f should be expected to decrease as the material type is varied from titanium to aluminum to steel. The fact that these void area tests show no difference in P_f as a function of striker plate material may indicate that the difference is negligibly small. Much more information and test data are required before the effect of material type can be established.

As was previously discussed, the thickness of the impacted material affects the size and intensity of the impact flash as well as its location relative to the plate (front or back side). A similar effect has been noted and described for the case of incendiary projectiles,[7] but the data cannot be extrapolated to inert fragments. If the material is very thin, the magnitude of the impact flash will be reduced, thereby potentially reducing P_f. A few ullage explosion tests were performed to compare the probability of an explosion with 0.2 inch titanium plates and 0.060 in. titanium plates. These tests are described in Section III and indicate that the effect of thickness on P_e is not very great under the conditions of those tests.

All of the void area tests were performed with unpainted striker and entrance plates. The effect of paint on P_f was initially considered to be negligible. The work reported in Reference 2 demonstrates that relatively thick coatings (about 0.030 in. and greater) of various materials on the front side of a plate can greatly reduce the impact flash on the back side of the plate. However, the author of that report also concludes that aircraft paints have very little effect on the impact flash. Near the completion of this program, another test program being performed by a student at the Air Force Institute of Technology, and supported by the Flight Dynamics Laboratory, obtained preliminary results indicating that aircraft paints could affect impact flashes under the conditions of his tests. In order to quickly and very superficially assess the effect of this parameter, ten uninerted ullage tests were performed with painted entrance plates. These are described in Section III. The test results indicate that the paint had no effect on P_e, and the high speed film data showed no decrease in impact flash intensity or size. However, these tests are too few and too limited in scope to provide a basis for entirely eliminating paint on the impacted plate as a significant variable.

Angle of Obliquity

The angle between the fragment's path and a normal to the striker plate (simulated aircraft skin) projected from the point of impact is the angle of obliquity. All of the tests performed in this program had a zero degree angle of obliquity. Consequently, nothing can be concluded regarding the effect of obliquity on P_f as a result of this program. Another program[6] obtained results that indicate that P_f increases with the angle of obliquity for fragment impacts at about 5,000 ft/sec on a two-inch void area between 0.090 in. 2024-T3 aluminum sheets. Considerable data is available regarding the effect of obliquity on P_f for incendiary projectiles and demonstrating an increase in P_f with obliquity. Insufficient data exists to quantitatively estimate the effect of obliquity on the probability of fires initiated by fragment impacts.

Airflow

The effect of airflow on the probability of ignition and the sustenance of a fire on the external surface (integral fuel tank) of an aircraft has been discussed. The effect of airflow on P_f within a void area is considerably more complex. Although it is doubtful that airflow along the outer skin of an aircraft can affect the probability of ignition within a void area, the airflow can most definitely affect the sustenance of a void area fire. If the void area is unventilated and the fragment damage to the outer aircraft skin is slight, as was observed in these void area tests, the effect of airflow may be relatively unimportant. However, if the airflow within the void is significant, due to designed void area ventilation or large structural damage to the aircraft skin, the airflow may significantly affect the fire. Also, the initial reaction within the void may occur rapidly enough to produce an overpressure within the void that is capable of damaging or blowing off the aircraft skin. This was observed in the testing reported in Reference 4. One of the most important effects of airflow may be the prevention of the concentration of the combustion products within a void which could smother the fire. The void area tests described in this report were performed with only a striker and entrance plate forming the void; that is, the void was open to the atmosphere. This configuration effectively prevented any fire that was initiated from smothering itself, thereby providing a worst case test situation. It seems doubtful that airflow could increase the values of P_f obtained in this program; it may merely prevent fires from smothering themselves within actual dry bays.

In order to suppress void area fires on aircraft, the use of rapidly discharged chemical extinguishants is being considered. The effect of airflow on the capability of the extinguishant system to suppress fires initiated by projectile impacts may be considerable.[26] Some data on extinguishant agent requirements as influenced by airflow is available from engine nacelle fire extinguishment tests.

In the absence of additional test data, it is recommended that any effects of airflow on void area fires be neglected in deciding the values of P_f to be utilized in a vulnerability analysis.

Other Combat Threats

The only fragment utilized in these void area tests was the 180 grain hexagonal fragment. Other void area fire test programs utilizing different fragments have been performed under different test conditions and, therefore, may not be suitable for comparison with the results of this test program. A comparison of the effects of the 180 grain hexagonal fragment and two other fragments on the probability of a fuel tank explosion is made in Section III. This comparison cannot be applied to void area tests.

Many void area fire test programs have been performed utilizing incendiary rounds. In general, if the aircraft skin materials, projectile velocity, and/or the angle of obliquity are sufficient to cause the incendiary to properly function, the probability of a fuel fire is greater than for a fragment impact.

Altitude

Several investigators have concluded that fuel fires can occur at altitudes greater than 60,000 feet. Earlier data indicates that P_f is not significantly altered between sea level and 20,000 feet for incendiary threats.[5] A more recent report claims that P_f decreases with altitude and that the initiation of a fire with fragments is virtually impossible above some intermediate altitude. Reference 2 claims that impact flashes decrease with altitude, but the effect is not significant below 60,000 feet. Also, the hot surface ignition temperatures and the minimum spark ignition energy are known to increase with altitude.[8,9] Although it is generally agreed that P_f decreases with altitude, this effect may be insignificant. Insufficient data is available to attempt to quantitatively estimate this effect. The data obtained in this program applies to a near sea level condition and represents a worst case test condition with regard to altitude.

Fuel and Air Temperature

The liquid fuel spray or mist entering the void area immediately after impact must evaporate to some extent before it can be ignited. Since the rate of evaporation of the liquid fuel spray will increase with the liquid fuel temperature and void area air temperature, it seems reasonable to conclude that P_f will increase with increasing fuel and air temperature. The vapor pressure of the fuel should similarly affect P_f. The very large number of tests performed by the Air Force Aero Propulsion Laboratory to evaluate the relative safety of several fuels indicates that the liquid fuel temperature and ambient air temperature weakly influence P_f for high volatility fuels such as JP-4. The effect of fuel temperature may be greater with lower volatility fuels such as JP-8 and JP-5. The void area tests described in this report were performed with liquid fuel temperatures of about 90°F ± 10°F. The ambient air temperature varied from about 40°F to 90°F.

Multiple Hits

In the event of simultaneous hits it is recommended that these events be considered to be independent if the impacts are far enough apart to prevent interactions. If the impacts occur at nearly the same location, they may increase P_f above the value obtained by assuming the events to be independent. However, there is insufficient data to make any quantitative judgment regarding simultaneous multiple impacts.

Utilizing This Test Data

In general, it is recommended that the values of P_f presented in Figure 5 be utilized in vulnerability analyses and that those results be modified, if necessary, to reflect different conditions, as described above, or to reflect the results of additional test data as it becomes available. Another consideration should be the possibility of ignition of the fuel pouring into a void area due to other ignition sources, such as hot surfaces, within the void area. Ignition by hot surfaces is influenced by the surface temperature, surface area, contact time, type of fuel, altitude, and fuel temperature. The minimum autoignition temperature of JP-4 is approximately 460°F in air at one atmosphere pressure.

Section III

UNINERTED ULLAGE TESTS

FUEL TANK EXPLOSIONS

Explosions of aircraft fuel tanks occur as a result of a very rapid pressure rise within the fuel tank. The pressure rise is due to the combustion of fuel vapors in the ullage (space above the liquid fuel) of the fuel tank. This combustion consists of the rapid propagation of a flame throughout the ullage and is normally a deflagration rather than a detonation. The effect of a fuel tank explosion ranges from a major structural failure to the rupture of a portion of the aircraft skin or fuel tank wall. Fuel tank explosions may then be followed by a fire.

The concentration of fuel vapors in the ullage is determined primarily by the fuel vapor pressure and the temperature f the liquid fuel generating these vapors. When the partial pressure of fuel vapors throughout the ullage is equal to the vapor pressure of the liquid fuel, the vapor mixture is said to be in equilibrium with the liquid. This is a difficult condition to achieve in the laboratory, and its occurrence within an aircraft fuel tank is probably unusual. The difficulties with the techniques and their use to achieve equilibrium in the JP-4 vapor combustion tests are described in Section V. The problem of determining the actual fuel vapor concentration within an aircraft fuel tank under any given set of flight conditions is probably the most difficult, and the most important, task involved in the establishment of values of P_e.

When a fragment passes through the ullage of a fuel tank, the fragment and/or the impact flashes at the point of entrance and exit to the tank are the sources of ignition of the fuel vapors. Therefore, any parameter affecting these impact flashes could thereby affect P_e. Some of these parameters are fragment size, shape, weight, velocity, angle of obliquity, and fuel tank wall material type and thickness.

TEST CONDITIONS

The objective of these uninerted ullage tests was to define explosion hazards in the ullage of an undefended fuel tank in terms of the probability of an explosion (P_e) versus the fuel vapor concentration, the fragment size, the fragment velocity, and the entrance plate material. A few tests were also performed to rudimentarily evaluate the effects of entrance plate thickness and painted entrance plates.

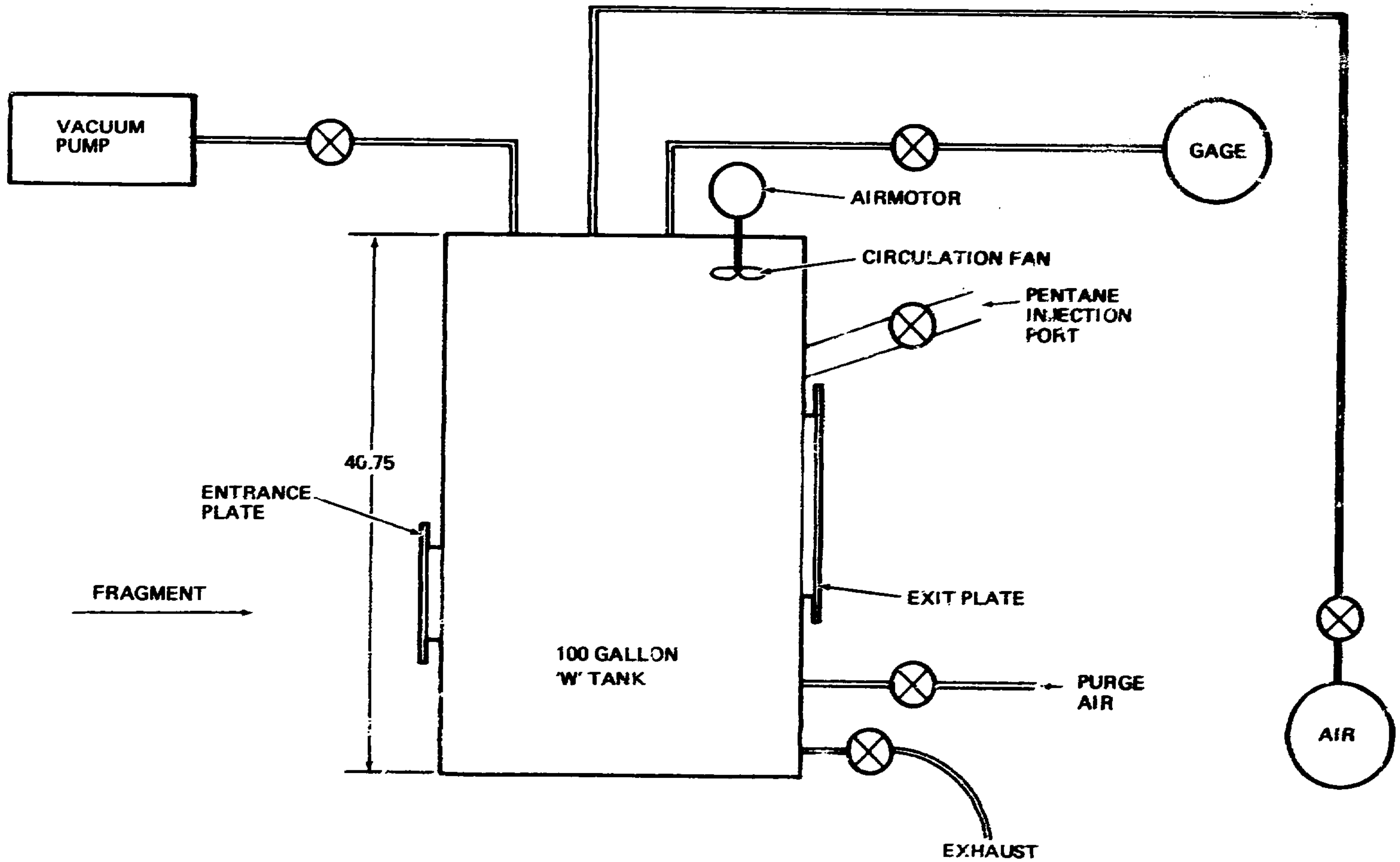
The fragments utilized in these tests were the 180 grain and 90 grain fragments previously described and shown in Figure 1. A few tests were also performed with the diamond shaped fragment to provide an evaluation of the effect of fragment shape. The fragment velocities tested in the uninerted ullage tests were varied over three discrete levels for both of the hexagonal fragments, as shown below:

	Velocities (ft/sec) ± 250		
	Low	Intermediate	High
180 grain fragments (diamond and hexagon)	3750	4750	5750
90 grain fragments	2750	4750	5750

These velocities were chosen by survivability engineers to represent the impact velocities of fragments from warheads detonating at various distances from the aircraft. The fragments impacted the entrance plate normal to its surface, that is, at a zero angle of obliquity. The entrance plates used in these tests were either 0.060 in. 6Al-4V titanium or 0.090 in. 2024-T3 aluminum, except for a very few tests performed with 0.200 in. 6Al-4V titanium plates. No striker plates were used in these uninerted ullage tests. A few tests were performed with painted titanium and aluminum entrance plates. The paint used was an aliphatic polyurethane two-part reactant and pigmented resin base.

Normal pentane vapors were the fuel in these tests. The quantity of liquid pentane required to produce a given pentane concentration within the test tank was calculated and injected into the tank. The calculations are shown in Appendix I. The test tank was equipped with a fan to aid in the evaporation of the liquid pentane and to maintain a homogeneous mixture within the tank. Since the pentane vapors are heavier than air, these vapors have a tendency to settle to the bottom of the tank under extremely quiescent conditions. The fan prevented this from occurring. The liquid pentane always appeared to completely evaporate. The pressure was monitored during evaporation and the pressure rise was always that which would be expected from the complete evaporation of the pentane. Also, the partial pressure of pentane vapors in these tests was always far below the vapor pressure of the pentane liquid. All these tests were performed at 16.2 psia, simulating a 1.5 psig pressurized fuel tank at sea level. It was necessary to use pentane in these tests, instead of JP-4, due to the great difficulty involved in attaining the desired equilibrium fuel vapor concentrations with JP-4 and to the greatly increased test time that would be required with JP-4. This is explained in detail in Section V. Also, Section V contains a comparison of the combustion effects of JP-4 and pentane vapors. The fuel vapor concentrations were varied from near stoichiometric (2.6%) to 7% by volume, thereby simulating some of the richer fuel vapor concentrations that would be anticipated within the fuel tanks of aircraft under equilibrium conditions.

The test article was a 98 gallon, rectangular, reinforced steel tank. The entrance plate retaining ring, entrance hole, and O-ring seal were identical to the entrance plate assembly used in the void area tests. This tank was also used for the aluminum/aluminum void area test configuration. A drawing of the test article and all related test equipment is shown in Figure 6. The fragment was not trapped within the tank as in the void area tests. The stopping of the fragment was deemed unrealistic for these explosion tests, and doing this might have provided an additional and unrealistic ignition source in the form of the spent, but probably hot, fragment. Therefore, the fragments were allowed to penetrate a 0.090 in. 2024-T3 aluminum exit plate. The possibility of an ignition due to fragment penetration of this exit sheet was considered unlikely, primarily because the exit plate impact flash would be predominantly on the back side of the exit plate, and therefore outside of the



INSTRUMENTATION: HIGH SPEED MOTION PICTURE COVERAGE
PRESSURE TRANSDUCER; THERMOCOUPLES

FIGURE 6. UNINERTED ULLAGE TEST SETUP

test tank. Also, the fragment's velocity would always be less at the exit plate than at the entrance plate.

The test tank was also equipped with a thermocouple and a strain gage pressure transducer. The test tank temperature was required in the calculation of the quantity of liquid pentane that must be injected into the tank in order to obtain the desired fuel vapor concentration. The pressure transducer merely confirmed the occurrence of an explosion. High speed motion picture coverage (nominally 7,000 frames/sec) of the events occurring within the test tank was also obtained.

UNINERTED ULLAGE TEST PROCEDURE

The test procedure for the uninerted ullage test series was as follows:

1. Bolt the desired entrance plate on front of test article and a standard 0.090 in. 2024-T3 aluminum exit plate on rear.
2. Record ambient tank temperature.
3. Vacuum test article to less than 2 psia.
4. Record test number, date, time of test, entrance plate used, desired pentane concentration, and pressure before adding pentane.
5. Using test tank temperature from step 2 and desired pentane concentration, calculate amount of pentane liquid required for test.
6. Inject pentane into test article.
7. Request gun range Safety Officer to clear test area of unnecessary personnel so that gun may be loaded and test article pressurized.
8. Start circulation fan.
9. Record pressure increase due to evaporated pentane.
10. Pressurize test article to 16.20 psia and check temperature to ensure correct mixing temperature.
11. Allow fan to circulate gas mixture for several minutes.
12. Close pressure gage port.
13. Five seconds before firing, turn off circulation fan.
14. Two seconds before firing, start pressure oscillograph.
15. After shot has occurred, record fragment velocity, explosion or no explosion, and overpressure.

16. Purge test article of residual vapors with shop air for several minutes.
17. When range has been cleared, recycle test article.

UNINERTED ULLAGE TEST DATA AND RESULTS

The compiled data from these tests are shown in Table II. The column headed ΔP contains the values of the peak combustion overpressure as measured on the pressure versus time traces obtained from the oscillograph recording of the pressure transducer signal. The column headed Δt_R contains the values of the time required for the pressure to rise to the peak value, beginning at the point where the pressure first begins to rise. In some tests, particularly the richer mixtures, a considerable length of time passed between fragment impact and the start of pressurization within the tank. This time is shown in the column headed Δt_D. The time from fragment impact to the peak overpressure is $\Delta t_R + \Delta t_D$. In some tests the chronograph system failed, and the velocities of the fragments are estimated based upon the shell loadings. When the velocities could not be estimated, they were listed as unknown and were not used in the analysis of the data.

When analyzing this test data, all fragment velocities within about 250 feet per second of the desired velocity were considered satisfactory. Also, pentane vapor concentrations within one tenth of a percent of the desired value were similarly "lumped together." The slight deviation in pentane vapor concentrations was due to errors in the amount of air added and temperature variations. These errors were known and measured, and the volume percent of pentane was corrected to take them into account.

The high speed motion picture films of the inside of the test tank were especially useful in comparing the impact flashes and hot particles generated by impacts on the aluminum and titanium entrance plates. First, there did not appear to be any great difference in the impact flashes with either entrance plate material. The duration of the impact flash varied from about 1.5 to about 2.5 msec for both the titanium and the aluminum entrance plates. Based upon the observations of the void area tests, it was expected that the impact

TABLE II

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
1	Unknown	3787 FPS	180 Grain Hexagonal Frag.- Low Velocity .060 6AL-4V Titanium	Yes	NA			Pressure Transducer Malfunction
2	2.8	3809 FPS	"	Yes	125	.02	0	
3	2.7	3891 FPS	"	Yes	122	.04	0	
4	2.7	3790 FPS	"	Yes	125	.04	0	
5	2.8	3853 FPS	"	Yes	128	.04	0	
6	2.7	3831 FPS	.090 2024-T3 Aluminum	Yes	128	.04	0	
7	2.7	3816 FPS	"	Yes	122	.06	0	
8	2.7	3838 FPS	"	Yes	120	.05	0	
9	2.7	3868 FPS	"	Yes	NA			Pressure Transducer Malfunction
10	2.7	3724 FPS	"	Yes	120	.06	0	
11	8.7	3731 FPS	"	No				
12	7.0	3937 FPS	.060 6AL-4V Titanium	No				
13	7.0	3937 FPS	.090 2024-T3 Aluminum	No				
14	5.6	3906 FPS	.060 6AL-4V Titanium	No				
15	5.4	Unknown	.090 2024-T3 Aluminum	No				
16	5.6	3831 FPS	.060 6AL-4V Titanium	Yes	45	.14	.51	
17	5.4	3913 FPS	.090 2024-T3 Aluminum	No				
18	5.4	4024 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			180 Grain Hexagonal Frag.- Low Velocity					
19	5.4	3992 FPS	.060 6AL-4V Titanium	No				
20	5.4	4106 FPS	"	No				
21	5.4	3921 FPS	"	Yes	40	.21	.61	
22	5.4	3883 FPS	"	Yes	42	.24	.20	
23	5.4	3705 FPS	"	Yes	28	.42	.52	
24	5.4	Unknown	.090 2024-T3 Aluminum	No				
25	5.4	4008 FPS	"	No				
26	5.3	3913 FPS	"	No				
27	5.3	38[illegible]8 FPS	.060 6AL-4V Titanium	Yes	34	.33	.27	

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	Δt_R (SEC)	Δt_D (SEC)	REMARKS
			180 Grain Hexagonal Frag.- Low Velocity					
28	4.9	3752 FPS	.060 6AL-4V Titanium	Yes	NA			
29	4.7	3780 FPS	"	Yes	45	.19	.01	
30	4.8	3738 FPS	"	Yes	45	.15	0	
31	4.8	3838 FPS	"	Yes	35	.30	.09	
32	4.8	3875 FPS	"	Yes	40	.33	.09	
33	4.9	3656 FPS	.090 2024-T3 Aluminum	No				
34	4.9	3703 FPS	"	Yes	40	.24	0	
35	4.8	3703 FPS	"	No				
36	4.8	3361 FPS	"	Yes	43	.20	0	considered to be a good test despite low velocity
37	4.8	3514 FPS	"	No				
38	4.8	3603 FPS	"	No				
39	4.8	3750 FPS (est)	"	No				
40	4.8	3750 FPS (est)	"	No				
41	4.8	3707 FPS	"	No				
42	4.8	3539 FPS	"	Yes	45	.15	.03	
43	6.4	3750 FPS (est)	.060 6AL-4V Titanium	Yes	23	.69	.02	
44	6.4	3750 FPS (est)	"	No				
45	6.4	3623 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			180 Grain Hexagonal Frag.-Low Velocity					
46	6.4	3597 FPS	.060 6AL-4V Titanium	No				
47	6.4	3696 FPS	"	No				
48	6.4	3710 FPS	"	No				
49	6.4	3750 FPS (est)	"	No				
50	6.4	3527 FPS	"	No				
51	6.4	3577 FPS	"	No				
52	6.4	3629 FPS	"	No				
53	5.3	3710 FPS	"	Yes	NA			Pressure Transducer Malfunction
54	5.3	3696 FPS	"	Yes	60	.69	.23	
55	5.4	3787 FPS	"	Yes	55	.53	.24	
56	5.4	3745 FPS	"	No				
57	3.8	3773 FPS	"	Yes	90	.15	.02	Sabot Entered Tank Not used for P_E data
58	3.8	3809 FPS	.090 2024-T3 Aluminum	Yes	100	.08	0	
59	3.8	3816 FPS	"	No				
60	3.8	3838 FPS	"	No				
61	3.7	3610 FPS	"	Yes	105	.05	0	
62	3.8	3676 FPS	"	Yes	95	.08	0	
63	3.8	3750 FPS (est)	"	Yes	95	.06	0	

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			180 Grain Hexagonal Frag.- Low Velocity					
64	3.7	3663 FPS	.090 2024-T3 Aluminum	Yes	98	.07	0	
65	3.8	3717 FPS	"	No				
66	3.7	3824 FPS	"	Yes	98	.07	0	
67	3.7	3809 FPS	"	Yes	112	.09	0	
			180 Grain Hexagonal Frag.-High Velocity					
68	6.4	Unknown	.090 2024-T3 Aluminum	No				
69	6.4	Unknown	"	No				
70	6.4	Unknown	"	No				
71	6.4	Unknown	"	No				
72	6.4	Unknown	"	No				
73	6.4	Unknown	.060 6AL-4V Titanium	Yes	NA			Pressure Transducer Malfunction
74	6.4	Unknown	.090 2024-T3 Aluminum	No				
75	6.4	Unknown	.060 6AL-4V Titanium	No				
76	6.4	Unknown	"	Yes	45	.35	.77	
77	6.4	Unknown	"	No				
78	6.4	Unknown	"	No				
79	6.4	Unknown	"	Yes	25	.43	.56	
80	6.4	Unknown	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
81	6.4	Unknown	180 Grain Hexagonal Frag.-High Velocity .060 6AL-4V Titanium	Yes	45	.59	1.37	
82	6.4	Unknown	"	Yes	42.5	.47	.89	
83	6.4	Unknown	"	No				
84								No Test
85	6.4	5730 FPS	"	No				
86	6.4	5847 FPS	"	Yes	30	.49	.89	
87	6.4	5797 FPS	"	No				
88	6.5	5917 FPS	"	No				
89	6.5	5763 FPS	"	No				
90	6.5	5813 FPS	"	No				
91	6.4	6006 FPS	"	Yes	NA			Pressure Transducer Malfunction
92	6.4	5934 FPS	"	No				
93	6.4	6006 FPS	"	No				
94	6.4	5830 FPS	"	Yes	30	.66	1.03	
95	6.4	5899 FPS	.090 2024-T3 Aluminum	No				
96	6.3	5780 FPS	"	No				
97	6.4	5681 FPS	"	No				
98	6.3	5988 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
99	6.3	6006 FPS	180 Grain Hexagonal Frag.-High Velocity .090 2024-T3 Aluminum	No				
100	5.9	5988 FPS	.060 6AL-4V Titanium	Yes	45	.35	.80	
101	5.9	5848 FPS	"	Yes	45	.33	.55	
102	5.9	5952 FPS	"	Nc				
103	5.9	5934 FPS	"	No				
104	5.8	58[illegible]9 FPS	"	No				
105	5.8	5882 FPS	"	Yes	55	.38	.47	
106	5.8	5899 FPS	"	No				
107	5.8	5882 FPS	"	No				
108	5.8	6134 FPS	"	Yes	40	.69	1.01	considered to be a good test despite high velocity
109	5.8	5700 FPS	(est) "	Yes	45	.39	.77	
110	5.4	5747 FPS	"	Yes	65	.32	.36	
111	5.4	5882 FPS	"	Yes	65	.21	.39	
112	5.3	5917 FPS	"	Yes	50	.28	.42	Pressure Transducer Malfunction
113	5.3	5882 FPS	"	Yes	NA			"
114	5.4	5882 FPS	"	Yes	NA			"
115	4.3	5952 FPS	.090 2024-T3 Aluminum	Yes	NA			"
116	4.3	5813 FPS	"	Yes	NA			"

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
117	4.2	5798 FPS	180 Grain Hexagonal Frag.-High Velocity .090 2024-T3 Aluminum	Yes	NA			Pressure Transducer Malfunction
118	4.2	5747 FPS	"	Yes	NA			"
119	4.2	5730 FPS	"	Yes	NA			"
120	4.8	5649 FPS	"	Yes	95	.24	0	
121	4.8	5988 FPS	"	Yes	95	.17	0	
122	4.9	5797 FPS	"	Yes	65	.34	0	
123	4.8	5780 FPS	"	Yes	90	.17	0	
124	4.8	5780 FPS	"	Yes	100	.18	0	
125	6.9	5797 FPS	.060 6AL-4V Titanium	No				
126	6.8	5797 FPS	"	No				
127	6.9	5813 FPS	"	No				
128	6.9	5899 FPS	"	No				
129	6.9	5899 FPS	"	No				
130	5.3	5813 FPS	.090 2024-T3 Aluminum	Yes	70	.24	0	
131	5.3	5797 FPS	"	No				
132	5.3	5882 FPS	"	Yes	70	.39	0	
133	5.3	5847 FPS	"	No				
134	5.3	5934 FPS	"	Yes	NA			Pressure Transducer Malfunction

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
135			180 Grain Hexagonal Frag.-High Velocity					No Test
136	5.3	5917 FPS	.090 2024-T3 Aluminum	Yes	NA			Pressure Transducer Malfunction
137	5.3	5917 FPS	"	Yes	NA			"
138	5.3	6079 FPS	"	No				Considered to be Good Tests Despite
139	5.3	6042 FPS	"	No				Slightly High Velocity
140	5.3	5405 FPS	"	No				
141	3.7	2695 FPS	90 Grain Hexagonal Frag.- Low Velocity .090 2024-T3 Aluminum	Yes	NA			Pressure Transducer Malfunction
142	3.7	2617 FPS	"	Yes	107.5	.12	0	
143	3.7	2747 FPS	"	No				
144	3.7	2747 FPS	"	Yes	95	.16	0	
145	3.7	2739 FPS	"	Yes	97.5	.13	0	
146	3.7	2773 FPS	"	Yes	100	.13	0	
147	3.7	2762 FPS	"	No				
148	3.7	2770 FPS	"	Yes	102	.09	0	
149	3.7	2721 FPS	"	Yes	NA			Pressure Transducer Malfunction
150	3.7	2739 FPS	"	No				
151	4.8	2688 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			90 Grain Hexagonal Frag.- Low Velocity					
152	4.8	2781 FPS	.090 2024-T3 Aluminum	No				
153	4.8	2857 FPS	"	Yes	95	.25	0	
154	4.8	2906 FPS	"	No				
155	4.8	2890 FPS	"	No				
156	4.8	2793 FPS	"	No				
157	4.8	2853 FPS	"	No				
158	4.8	2750 FPS (est)	"	No				
159	4.8	2877 FPS	"	Yes	95	.24	0	
160	5.3	2635 FPS	.060 6AL-4V Titanium	Yes	70	.56	.26	
161	5.3	2645 FPS	"	Yes	NA			Pressure Transducer Malfunction
162	5.3	2789 FPS	"	Yes	68	.53	.32	
163	5.3	1047 FPS	"	No				No Test - Low Velocity
164	5.3	2857 FPS	"	Yes	70	.52	0	
165	5.3	2713 FPS	"	No				
166	5.3	2781 FPS	"	Yes	70	.51	.25	
167	5.3	2453 FPS	"	Yes	78	.41	.11	Considered Good Test
168	5.3	2544 FPS	"	No				
169	5.3	2728 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			90 Grain Hexagonal Frag.- Low Velocity					
170	5.9	2710 FPS	.060 6AL-4V Titanium	No				
171	5.9	2820 FPS	"	No				
172	5.9	2812 FPS	"	No				
173	5.9	2751 FPS	"	No				
174	5.9	2777 FPS	"	Yes	60	.58	0	
175	5.9	2793 FPS	"	Yes	65	.60	0	
176	5.9	2713 FPS	"	Yes	70	.44	0	
177	5.8	2758 FPS	"	No				
178	5.8	2604 FPS	"	No				
179	5.8	2695 FPS	"	Yes	65	.51	0	
180	4.7	2670 FPS	.090 2024-T3 Aluminum	No				
181	4.8	2699 FPS	"	No				
182	4.7	2770 FPS	"	No				
183	4.8	2754 FPS	"	No				
184	4.8	2758 FPS	"	Yes	93	.22	.03	
185	4.8	2820 FPS	"	No				
186	4.8	2797 FPS	"	No				
187	4.8	2750 FPS (est)	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			90 Grain Hexagonal Frag.- Low Velocity					
188								No Test
189	4.7	2836 FPS	.090 2024-T3 Aluminum	No				
190	4.7	2797 FPS	"	No				
191	4.7	2355 FPS	"	No				No Test Low Velocity
192	4.7	2695 FPS	"	No				
193	3.7	2677 FPS	"	No				
194	3.7	2728 FPS	"	No				
195	3.7	2873 FPS	"	Yes	100	.17	0	
196	3.7	2716 FPS	"	Yes	100	.18	0	
197	3.6	2865 FPS	"	Yes	95	.18	0	
198	3.7	2496 FPS	"	No				
199	3.7	2793 FPS	"	No				
200	3.7	2836 FPS	"	No				
201	4.8	2771 FPS	.060 6AL-4V Titanium	Yes	63.5	.28	.27	
202	4.8	2628 FPS	"	Yes	68.5	.41	.19	
203	4.8	2770 FPS	"	No				
204	4.8	2805 FPS	"	No				
205	4.8	2728 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
206	4.8	2824 FPS	90 Grain Hexagonal Frag.- Low Velocity .060 6AL-4V Titanium	Yes	86	.25	0	
207	4.8	2881 FPS	"	No				
208	4.8	2717 FPS	"	No				
209	4.8	2828 FPS	"	Yes	67.5	.41	.33	
210	4.8	2898 FPS	"	No				
211	4.8	2828 FPS	"	No				
212	4.8	2706 FPS	"	Yes	74	.31	.26	
213	4.7	2614 FPS	"	Yes	86	.31	0	
214	4.8	2642 FPS	"	No				
215	4.8	89 FPS	"	No				No Test - Low Velocity
216	4.8	2732 FPS	"	Yes	110	.13	0	
217	4.8	2710 FPS	"	Yes	71	.43	.33	
218	4.7	2732 FPS	"	No				
219	4.3	2594 FPS	"	Yes	109	.23	0	
220	4.3	2739 FPS	"	No				
221	4.3	2544 FPS	"	No				
222	4.2	2762 FPS	"	Yes	110	.15	0	
223	4.3	2638 FPS	"	Yes	110	.18	.15	

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
224	4.3	2739 FPS	90 Grain Hexagonal Frag.- Low Velocity .060 6AL-4V Titanium	Yes	98	.18	0	
225	4.2	2590 FPS	"	No				
226	4.3	2610 FPS	"	Yes	100	.20	.16	
227	4.3	2717 FPS	"	No				
228	4.2	2820 FPS	"	No				
229	3.7	2732 FPS	"	Yes	100	.14	0	
230	3.7	2695 FPS	"	Yes	100	.15	.06	
231	3.7	2721 FPS	"	No				
232	3.7	2816 FPS	"	Yes	115	.08	0	
233	3.7	1908 FPS	"	No				No Test - Low Velocity
234	3.7	1838 FPS	"	No				No Test - Low Velocity
235	3.7	2758 FPS	"	Yes	105	.12	0	
236	3.7	2706 FPS	"	No				
237	3.7	2886 FPS	"	Yes	107	.10	.08	
238	3.7	2762 FPS	"	Yes	107	.15	0	
239	3.7	2706 FPS	"	Yes	105	.15	0	
240	3.7	2793 FPS	"	No				
241	3.7	2439 FPS	"	Yes	102.5	.12	.08	Considered Good Despite Low Velocity

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			90 Grain Hexagonal Frag.-Low Velocity					
242	3.2	2773 FPS	.060 6AL-4V Titanium	Yes	92	.13	.08	
243	3.2	2816 FPS	"	Yes	100	.12	0	
244	3.2	2812 FPS	"	Yes	96	.11	.08	
245	3.2	2853 FPS	"	Yes	NA			Pressure Transducer Malfunction
246	3.2	2762 FPS	"	Yes	95	.11	.08	
247	3.2	2793 FPS	.090 2024-T3 Aluminum	Yes	100	.10	0	
248	3.2	2902 FPS	"	Yes	108	.09	0	
249	3.2	2789 FPS	"	No				
250	3.2	2525 FPS	"	Yes	105	.09	0	
251	3.2	2554 FPS	"	No				
252	3.2	2713 FPS	"	Yes	NA			Pressure Transducer Malfunction
253	3.2	2604 FPS	"	No				
254	3.2	2735 FPS	"	No				
255	3.2	2732 FPS	"	No				
256	3.2	2680 FPS	"	Yes	95	.12	0	
257	5.3	2659 FPS	.060 6AL-4V Titanium	No				
258	5.3	2793 FPS	"	Yes	115	.14	0	No Test - Pressurization Error
259	5.3	2706 FPS	"	Yes	63	.58	.46	

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
260	5.3	2478 FPS	90 Grain Hexagonal Frag.-Low Velocity .060 6AL-4V Titanium	Yes	72	.38	.16	Considered Good Test Despite Slightly Low Velocity
261	5.3	2316 FPS	"	Yes	82	.31	.08	
262	5.3	2853 FPS	"	No				
263	2.8	2594 FPS	.090 2024-T3 Aluminum	Yes	102	.15	0	
264	2.8	2751 FPS	"	No				
265	2.8	2724 FPS	"	No				
266	2.8	2580 FPS	"	Yes	104	.10	0	
267	2.8	2583 FPS	"	Yes	102	.11	.02	
268	6.3	5571 FPS	90 Grain Hexagonal Frag.-High Velocity .060 6AL-4V Titanium	No				
269	6.4	5602 FPS	"	No				
270	6.3	5730 FPS	"	Yes	65	.32	.32	
271	6.3	5681 FPS	"	Yes	49	.54	.96	
272	6.4	5797 FPS	"	Yes	46	.54	1.11	
273	6.4	5700 FPS (est)	"	Yes	53	.53	.69	
274	6.4	5640 FPS	"	Ye	70	.36	.40	
275	6.3	5649 FPS	"	Yes	70	.39	.42	
276	6.3	5449 FPS	"	Yes	62	.42	.56	
277	6.4	5665 FPS	"	Yes	45	.465	.55	

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
278	—	—	90 Grain Hexagonal Frag.- High Velocity .060 6AL-4V Titanium	—				No Test
279	7.4	5681 FPS	"	No				
280	7.4	5102 FPS	"	No				No Test - Low Velocity
281	7.4	5319 FPS	"	No				No Test - Low Velocity
282	7.4	5847 FPS	"	No				
283	7.4	5698 FPS	"	No				
284	7.4	5649 FPS	"	No				
285	5.3	5700 FPS (est)	"	Yes	83	.22	.22	
286	5.3	5698 FPS	"	Yes	86	.18	.15	
287	5.3	5681 FPS	"	Yes	72	.15	.16	
288	5.3	5750 FPS	.090 2024-T3 Aluminum	No				
289	5.3	5681 FPS	"	No				
290	5.3	5797 FPS	"	No				
291	5.3	5700 FPS (est)	"	Yes	75	.30	.12	
292	5.3	5681 FPS	"	No				
293	5.3	5714 FPS	"	Yes	75	.36	.13	
[illegible]	5.3	5730 FPS	"	No				
295	5.3	5747 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
296	5.3	5730 FPS	90 Grain Hexagonal Frag. - High Velocity .090 2024-T3 Aluminum	No				
297	5.2	5813 FPS	"	No				
298	4.2	3571 FPS	"	Yes	105	.10	0	No Test - Low Velocity
299	4.3	5970 FPS	"	Yes	85	.08	0	
300	4.2	Unknown	"	Yes	100	.11	0	No Test - Hit Striker Ring
301	4.2	5747 FPS	"	Yes	95	.07	0	
302	4.3	Unknown	"	—				No Test
303	4.2	5899 FPS	"	Yes	100	.07	0	
304	4.2	5988 FPS	"	No				
305	4.3	3616 FPS	"	No				No Test - Low Velocity
306	4.2	3034 FPS	"	Yes	105	.10	0	No Test - Low Velocity
307	4.2	NA	"	Yes	95	.20	.07	No Test
308	4.2	5917 FPS	"	Yes	100	.05	0	
309	4.2	4566 FPS	"	Yes	100	.13	0	No Test - Low Velocity
310	4.2	5780 FPS	"	Yes	100	.10	.07	
311	4.2	5952 FPS	"	Yes	100	.06	0	
312	4.2	5952 FPS	"	Yes	100	.09	0	
313	4.2	5847 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			90 Grain Hexagonal Frag.-High Velocity					
314	4.2	4796 FPS	.090 2024-T3 Aluminum	Yes	105	.10	0	No Test - Low Velocity
315	4.2	5494 FPS	"	No				Good Test Despite Slightly Low Velocity
316	4.2	4889 FPS	"	Yes	110	.10	0	No Test - Low Velocity
317	4.2	4424 FPS	"	Yes	108	.10	0	No Test - Low Velocity
318	4.2	5830 FPS	"	Yes	100	.10	0	
319	5.3	5797 FPS	.060 6AL-4V Titanium	Yes	83	.14	.21	
320	5.4	5899 FPS	"	Yes	NA			Pressure Transducer Malfunction
321	3.7	5865 FPS	.090 2024-T3 Aluminum	Yes	105	.05	0	
322	3.7	5813 FPS	"	Yes	105	.05	0	
323	3.7	5917 FPS	"	Yes	100	.05	0	
324	3.7	5818 FPS	"	Yes	105	.05	0	
325	3.7	5917 FPS	"	Yes	105	.06	0	
326	6.9	5882 FPS	.060 6AL-4V Titanium	No				
327	6.9	5882 FPS	"	No				
328	6.9	5790 FPS	"	No				
329	6.9	5847 FPS	"	No				
330	6.9	5830 FPS	"	No				
331	Unknown	5899 FPS	"	Yes	65	.55	.46	No Test - Pentane Injection Error

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
332	6.9	4273 FPS	90 Grain Hexagonal Frag.-High Velocity .060 6AL-4V Titanium	No				No Test - Low Velocity
333	6.9	4319 FPS	"	No				No Test - Low Velocity
334	6.4	4773 FPS	90 Grain Hexagonal Frag.-Inter.Velocity .060 6AL-4V Titanium	No				
335	6.4	4975 FPS	"	No				
336	6.3	4830 FPS	"	No				
337	6.4	4938 FPS	"	No				
338	6.4	4587 FPS	"	No				
339	4.8	4761 FPS	"	Yes	90	.15	.04	
340	4.8	4705 FPS	"	Yes	85	.16	.06	
341	4.8	4629 FPS	"	Yes	95	.11	.11	
342	4.8	4514 FPS	"	Yes	95	.11	.10	
343	4.8	4694 FPS	"	Yes	80	.16	.07	
344	4.8	4640 FPS	.090 2024-T3 Aluminum	Yes	80	.13	.05	
345	4.8	4807 FPS	"	Yes	77	.18	.06	
346	4.8	4773 FPS	"	Yes	80	.17	.04	
347	4.8	4938 FPS	"	Yes	80	.17	.06	
348	4.8	4914 FPS	"	Yes	85	.18	.06	
349	5.8	4705 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
350	5.8	4842 FPS	90 Grain Hexagonal Frag.-Inter.Velocity .090 2024-T3 Aluminum	No				
351	5.8	4784 FPS	"	No				
352	5.8	4842 FPS	"	No				
353	5.8	4889 FPS	"	No				
354	5.3	4784 FPS	"	Yes	75	.28	.13	
355	5.3	4705 FPS	"	No				
356	5.3	4728 FPS	"	No				
357	5.3	4629 FPS	"	Yes	83	.20	.05	
358	5.3	4672 FPS	"	No				
359	5.3	4807 FPS	"	No				
360	5.3	4761 FPS	"	No				
361	5.3	4866 FPS	"	No				
362	5.3	4854 FPS	"	No				
363	5.3	4889 FPS	"	Yes	67.5	.32	.15	
364	5.3	3649 FPS	180 Grain Hexagonal Frag.-Inter.Velocity .090 2024-T3 Aluminum	No				No Test - Low Velocity
365	5.3	3797 FPS	"	No				No Test - Low Velocity
366	5.3	4889 FPS	"	No				
367	5.3	5167 FPS	"	No				No Test - High Velocity

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
368	5.3	4866 FPS	180 Grain Hexagonal Frag. -Inter. Velocity .090 2024-T3 Aluminum	No				
369	5.3	4866 FPS	"	No				
370	5.3	4819 FPS	"	No				
371	4.3	4938 FPS	"	Yes	97	.08	0	
372	4.2	4854 FPS	"	Yes	92	.05	0	
373	4.2	4842 FPS	"	Yes	95	.08	0	
374	4.2	4975 FPS	"	Yes	100	.06	0	
375	4.2	4926 FPS	"	Yes	95	.08	0	
376	4.8	4938 FPS	"	Yes	70	.27	0	
377	4.8	4901 FPS	"	No				
378	4.8	5025 FPS	"	No				Considered Good Test Despite Slightly High Velocity
379	4.8	4962 FPS	"	Yes	70	.25	.10	
380	4.8	4962 FPS	"	No				
381	4.8	4936 FPS	"	No				
382	4.8	4901 FPS	"	Yes	68	.19	.12	
383	4.8	4962 FPS	"	No				
384	4.8	4889 FPS	"	No				
385	4.8	4914 FPS	"	No				

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
386	5.8	4282 FPS	180 Grain Hexagonal Frag.-High Velocity .200 6AL-4V Titanium	Yes	NA	Pressure Transducer Malfunction		No Test - Low Velocity
387	7.0	4484 FPS	"	No				No Test - Low Velocity
388	7.0	1994 FPS	"	No				No Test - Low Velocity
389	7.0	5405 FPS	"	No				*
390	7.0	5509 FPS	"	No				
391	7.0	5277 FPS	"	No				*
392	7.0	5376 FPS	"	No				*
393	7.0	5555 FPS	"	No				
394	5.8	2832 FPS	"	Yes	53	NA	NA	No Test - Low Velocity
395	5.8	5540 FPS	"	Yes	32	NA	NA	
396	5.8	5420 FPS	"	Yes	35	NA	NA	*
397	5.8	5555 FPS	"	Yes	50	NA	NA	
398	5.8	5617 FPS	"	Yes	NA			Pressure Transducer Malfunction
399	4.9	5550 FPS (EST)	.060 6AL-4V Titanium	Yes	85	NA	NA	
400	4.9	5555 FPS	Painted with 2 Part	Yes	65	NA	NA	
401	4.9	5550 FPS (EST)	Aliphatic Polyurethane and	Yes	65	NA	NA	
402	4.9	5550 FPS (EST)	Resin - "	Yes	50	NA	NA	
403	4.9	5550 FPS (EST)	"	Yes	65	NA	NA	

*These were considered to be good tests even though the velocities were slightly low.

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			180 Grain Diamond Frag.-High Velocity					
404	6.4	2398 FPS	.090 2024-T3 Aluminum	No	NA*			No Test - Low Velocity
405	6.4	Unknown	"	No	NA			
406	6.4	4008 FPS	"	No	NA			No Test - Low Velocity
407	6.4	6666 FPS	"	No	NA			Missed Tank - No Test
408	6.4	6349 FPS	"	No	NA			No Test - High Velocity
409	5.5	5681 FPS	"	No	NA			
410	5.5	5714 FPS	"	No	NA			
411	5.5	5555 FPS	"	No	NA			
412	5.5	5555 FPS	"	No	NA			
413	4.2	5571 FPS	"	Yes	NA			
414	4.2	5633 FPS	"	Yes	NA			
415	4.2	5681 FPS	"	Yes	NA			
416	5.5	5847 FPS	"	No	NA			
417	4.2	5698 FPS	"	Yes	NA			
418	4.2	5681 FPS	"	Yes	NA			
419	4.2	5797 FPS	.090 2024-T3 Aluminum Painted	Yes	NA			
420	4.2	5633 FPS	with 2 part Aliphatic Polyurethane	Yes	NA			
421	4.2	5865 FPS	and Resin "	Yes	NA			No Test - Frag. Hit Striker Ring

*Uncalibrated pressure transducer tests 375-404 used for verification of explosion only.

TABLE II (continued)

UNINERTED ULLAGE TESTS								
TEST NUMBER	VOLUME PERCENT PENTANE	FRAGMENT VELOCITY	ENTRANCE PLATE	EXPLOSION	ΔP (PSI)	ΔtR (SEC)	ΔtD (SEC)	REMARKS
			180 Grain Diamond Frag.-High Velocity					
422	4.2	5698 FPS	.090 2024-T3 Aluminum	Yes	NA			
423	4.2	5681 FPS	"	Yes	NA			
424	4.2	Unknown	.090 2024-T3 Aluminum	Yes	NA			No Test
425	5.0	5602 FPS	"	Yes	NA			
426	5.0	5617 FPS	"	Yes	NA			
427	5.0	5681 FPS	"	No	NA			
428	5.0	5665 FPS	"	No	NA			
429	5.0	5617 FPS	"	Yes	NA			
430	5.0	5633 FPS	"	Yes	NA			
431	5.0	5649 FPS	"	No	NA			
432	5.0	5700 FPS (est)	"	No	NA			
433	5.0	5665 FPS	"	Yes	NA			
434	5.0	5665 FPS	"	Yes	NA			

flash on the exit plate would occur primarily on the back side of the exit plate, that is, outside the test tank. Although impact flashes on the front side of the exit plate were observed within the test tank, these flashes were usually less intense and smaller than the impact flashes occurring on the back side of the entrance plate.

The impact of the fragment on the titanium plate caused a great number of large bright sparks (incandescent particles) to be generated which would linger within the tank for a very long time, often longer than a few hundred milliseconds. These sparks were not always noticed with the aluminum entrance plates, possibly because they were not bright enough to show up on the high speed film. When sparks were observed with the aluminum entrance plate, they were fewer in number, had a much shorter lifetime, and were less intense than those observed with the titanium entrance plate.

In many of these tests the ignition of the fuel vapors was immediate. However, in some tests, particularly those performed with higher fuel vapor concentrations, a considerable delay (Δt_D) in ignition was noted. The high speed camera sometimes ran out of film prior to ignition. The ignition source for these delayed reactions must have been the sparks, because the fragment and the impact flash were gone prior to ignition. Values of Δt_D often exceeded 500 msec, and in some tests the ignition delay time was greater than one second. These delays in ignition were more prevalent with the titanium entrance plates than with the aluminum entrance plates, and the delay times (Δt_D) were much shorter with the aluminum plates.

The damage to the entrance plate was consistently a hole of the same size and shape as the fragment. The exit plate damage was less consistent, indicating that the fragment may have tumbled within the tank. The exit plate damage often consisted of a number of smaller holes along with the hole made by the fragment. The fragments buried themselves in a sand bunker behind the test article and were not recovered. Based upon the exit plate damage and the few fragments recovered in the void area tests, it does not appear that the fragments broke apart to any great degree.

Five tests were performed at each set of test conditions. If the results of those five tests were consistent, i.e., all resulting in explosions or no explosions, testing of that set of conditions was terminated. If the results were not consistent, an additional five tests were performed with that set of test conditions, thereby providing ten tests on which to establish P_e. The results of the uninerted ullage tests are shown in Figures 7 through 10. These graphs depict P_e as a function of volume percent fuel vapor and the other variables tested. It must be pointed out that the values of P_e shown are relatively imprecise, even when ten tests have been performed to establish a single point on the graphs. Applying a confidence level of 90% to an individual data point results in a confidence interval greater than ± 0.2. This should be kept in mind when attempting to utilize this test data. Also, this data was obtained with pentane. Correlation to JP-4 is discussed in Section V.

The results of the 180 grain hexagonal fragment/titanium entrance plate tests (Figure 7) show only a small difference in P_e for the high and low velocities. Therefore, no intermediate velocity tests were performed. Increasing the thickness of the titanium entrance plate to 0.200 inch appeared to increase P_e slightly. There was no readily apparent difference in the impact flash within the test tank for the two titanium entrance plate thicknesses tested. The five tests performed with the painted titanium entrance plates showed no difference from the results that would be expected of unpainted plates. Also, the impact flashes within the tank appeared similar to those that occurred with unpainted entrance plates.

The tests performed with the 90 grain hexagonal fragment and the 0.060 in. titanium entrance plate (Figure 8) demonstrated a considerable difference between P_e values at the high and low velocities. The few tests performed under these conditions and at the intermediate velocity produced P_e values between the high and low velocity P_e values. The small fragment and the large fragment produced nearly identical results for the high velocity and titanium entrance plate test conditions. The small fragment appeared to be less of a threat at the lower velocity, but it must be remembered that the low velocities for the two fragments are not the same.

SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	180 GR. HEX	5750 FPS	.060 6AL-4V TITANIUM
▲	180 GR. HEX	3750 FPS	.060 6AL-4V TITANIUM
■	180 GR. HEX	5750 FPS	.200 6AL-4V TITANIUM
□	180 GR. HEX	5750 FPS	.060 6AL-4V TITANIUM (PAINTED)

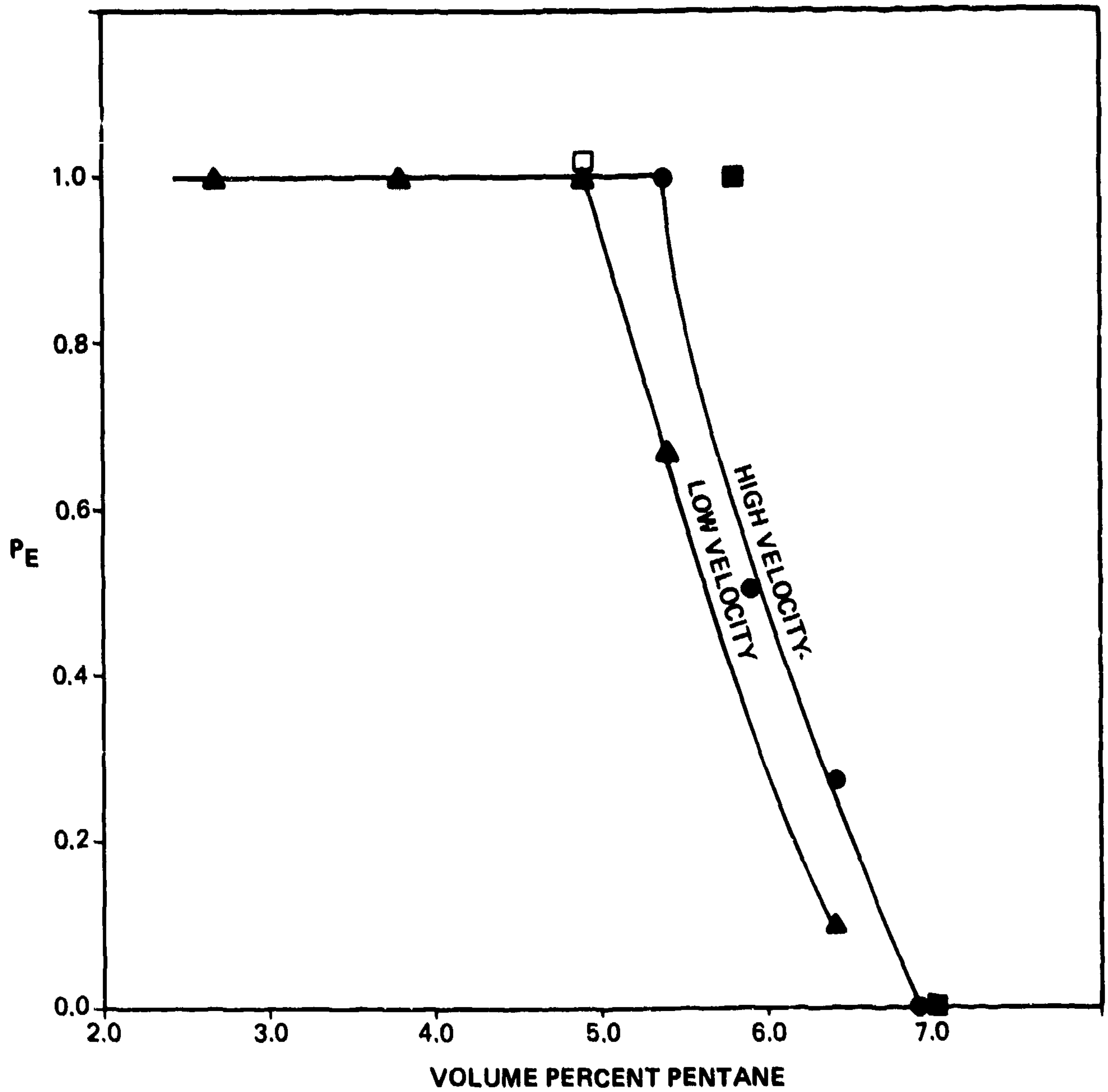
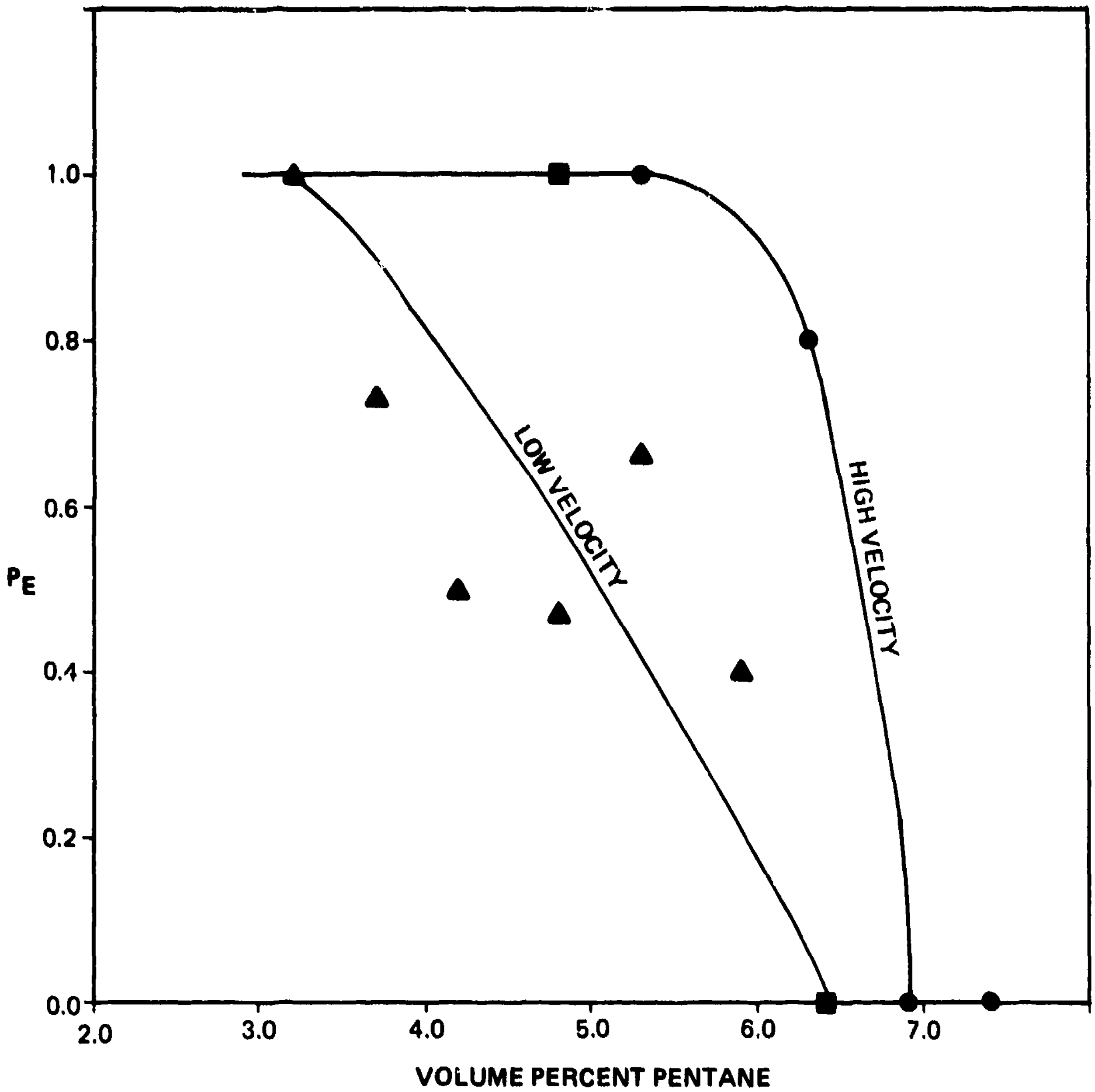
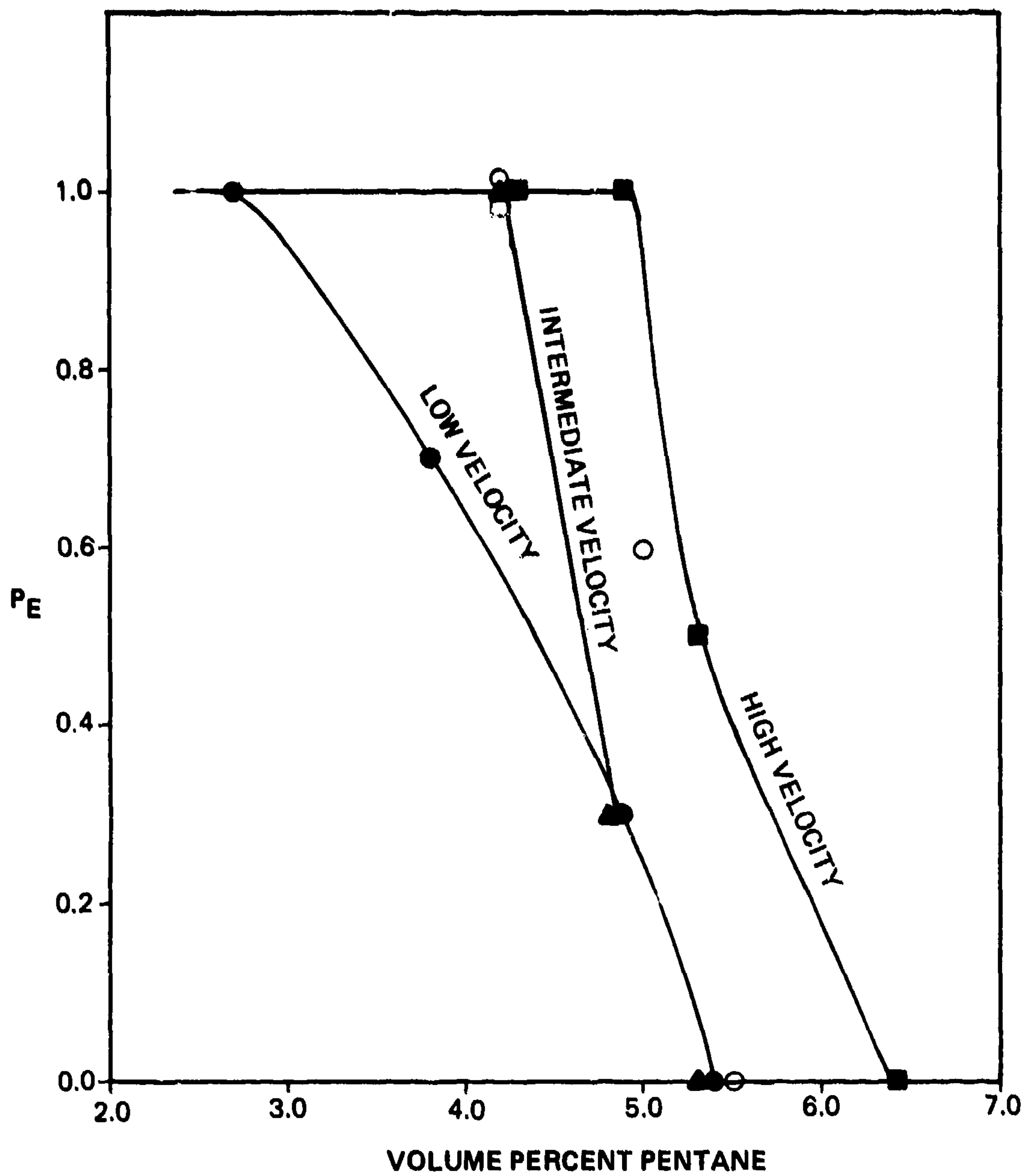


FIGURE 7. PROBABILITY OF EXPLOSION VS PERCENT PENTANE.



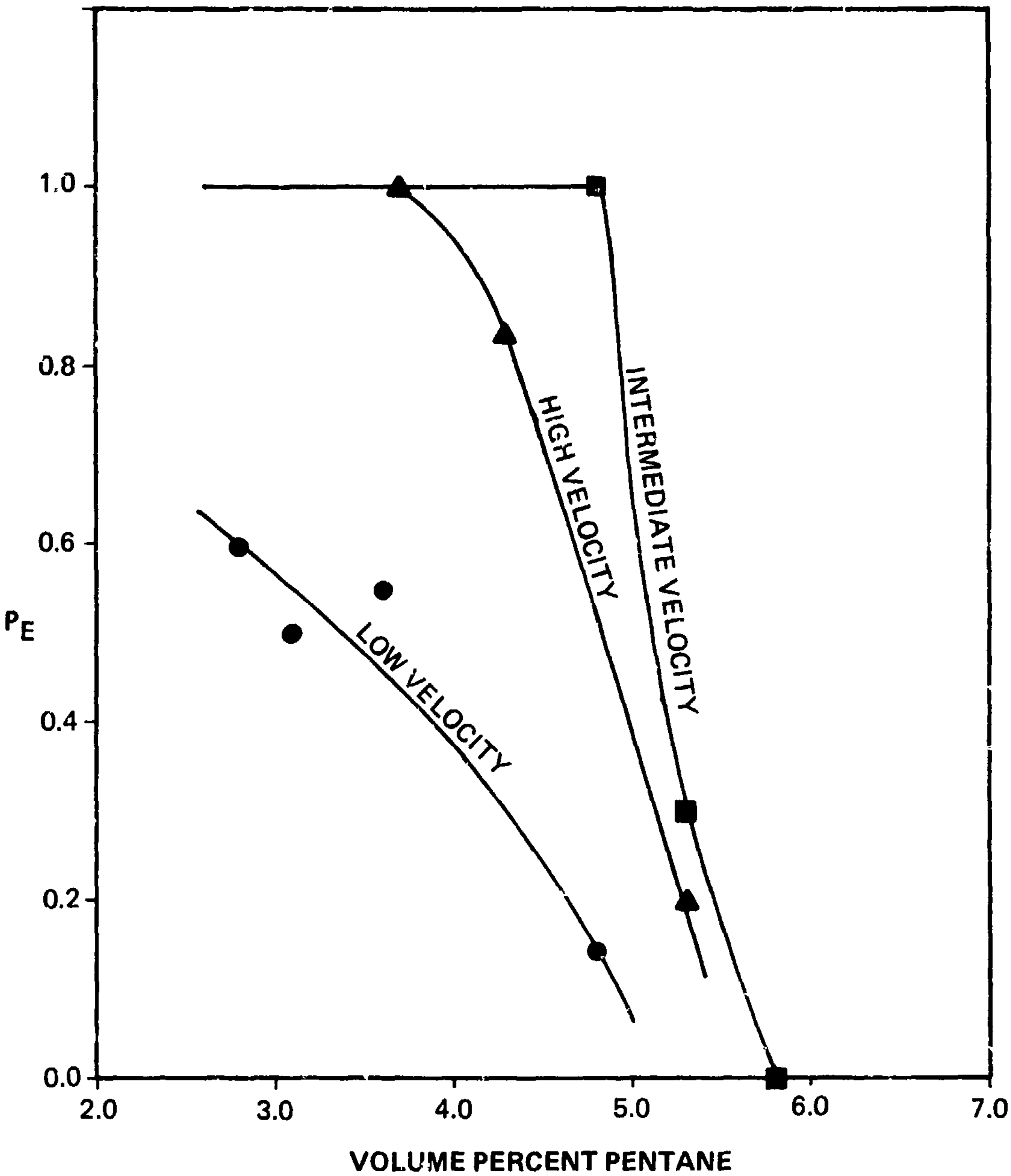
SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	90 GR. HEX	5750 FPS	.060 6AL-4V TI
▲	90 GR. HEX	2750 FPS	.060 6AL-4V TI
■	90 GR. HEX	4750 FPS	.060 6AL-4V TI

FIGURE 8. PROBABILITY OF EXPLOSION VS PERCENT PENTANE.



SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	180 GR. HEX	3750 FPS	.090 2024-T3 AL
▲	180 GR. HEX	4750 FPS	.090 2024-T3 AL
■	180 GR. HEX	5750 FPS	.090 2024-T3 AL
○	180 GR. DIAMOND	5750 FPS	.090 2024-T3 AL
□	180 GR. DIAMOND	5750 FPS	.090 2024-T3 AL PAINTED

FIGURE 9. PROBABILITY OF EXPLOSION VS PERCENT PENTANE.



SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	90 GR HEX	2750 FPS	.090 2024-T3 AL
▲	90 GR. HEX	5750 FPS	.090 2024-T3 AL
■	90 GR. HEX	4750 FPS	.090 2024-T3 AL

FIGURE 10. PROBABILITY OF EXPLOSION VS PERCENT PENTANE.

The tests performed with the large fragment and the aluminum entrance plate (Figure 9) demonstrate an increase in P_e with increasing fragment velocity. These test results also demonstrate slightly lower values of P_e for the diamond shaped fragment. Also, the few tests performed with the painted entrance plates produced the results that would be anticipated with unpainted plates. A comparison of Figures 7 and 9 shows that the use of aluminum entrance plates appears to reduce P_e as compared to the titanium plates.

The 90 grain hexagonal fragment/aluminum entrance plate tests (Figure 10) demonstrate very interesting results with regard to the velocity variable. The intermediate velocity tests resulted in higher P_e values than the high velocity tests. It is not scientifically impossible that the intermediate velocity is more severe than the higher velocity, due to fragment dwell time within the tank and/or the type, size, and duration of the sparks produced at different velocities. However, based upon the previous results at the intermediate velocity and the amount of energy available for ignition as a function of velocity, this result seems unlikely. It may be more reasonable to conclude that this merely demonstrates the low confidence associated with these test results, due to the relatively few number of tests (five or ten) performed at each condition. It should also be noted that the 90 grain hexagonal fragment/aluminum entrance/low velocity test condition was the only condition which did not produce a P_e of one at some tested fuel vapor concentration. A comparison of Figures 8 and 10 demonstrates the higher values of P_e that were obtained with the titanium entrance plate as compared to the aluminum entrance plate.

The peak combustion overpressures attained with a given set of test conditions have been averaged and are shown in Figure 11. Similarly, the overpressure rise times (Δt_R) have been averaged for each set of test conditions and are shown in Figure 12. These rise times are measured from the point at which the pressure begins to rise until the peak overpressure is attained, and do not include the time from impact to the start of the pressure rise (Δt_D). Two representative pressure traces are shown in Figure 13.

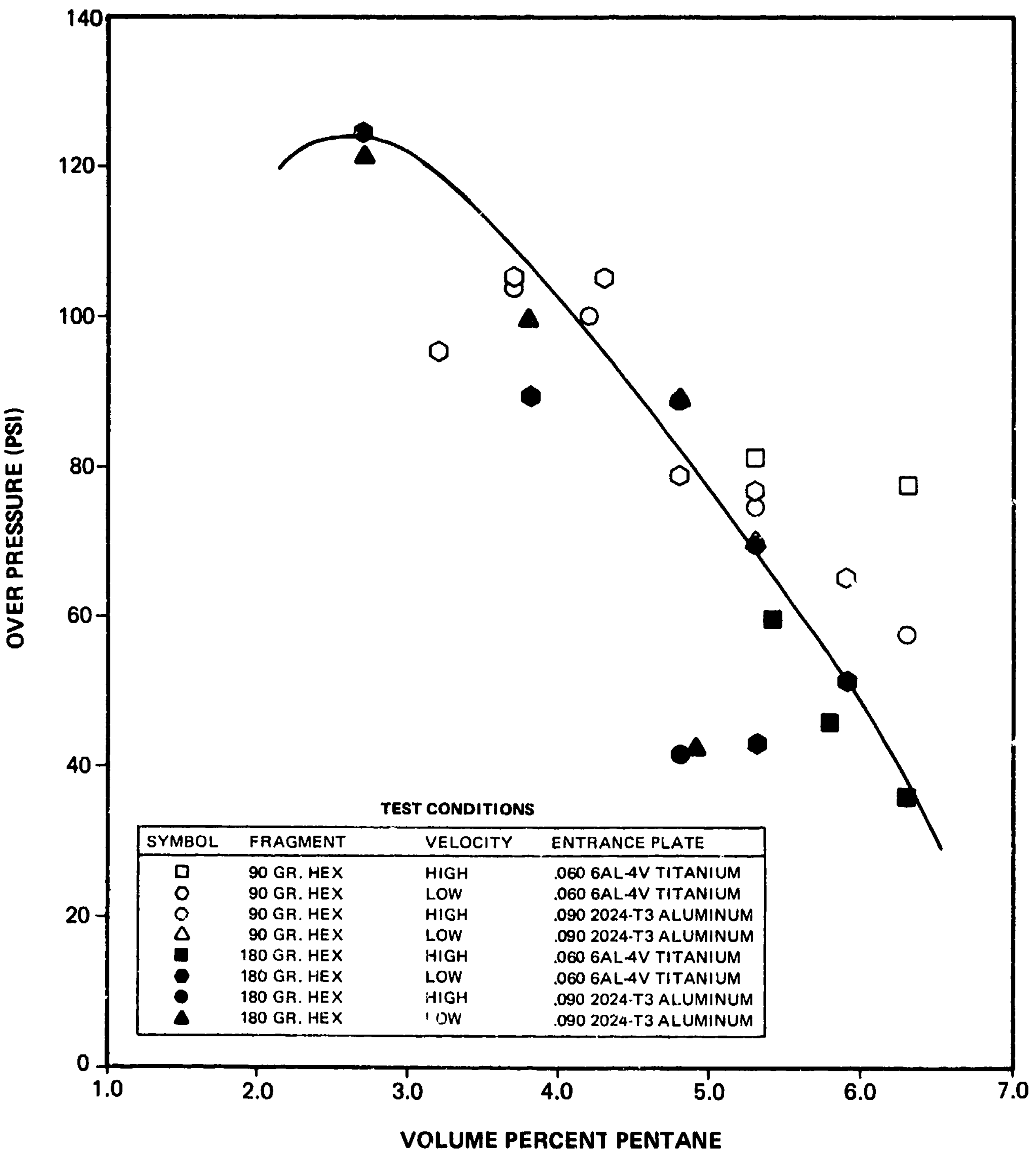


FIGURE 11. AVERAGE OVERPRESSURE VS PERCENT PENTANE FOR UNINERTED ULLAGE EXPLOSIONS.

TEST CONDITIONS

SYMBOL	FRAGMENT	VELOCITY	ENTRANCE PLATE
□	90 GR. HEX	HIGH	.060 6AL-4V TITANIUM
⬡	90 GR. HEX	LOW	.060 6AL-4V TITANIUM
○	90 GR. HEX	HIGH	.090 2024-T3 ALUMINUM
△	90 GR. HEX	LOW	.090 2024-T3 ALUMINUM
■	180 GR. HEX	HIGH	.060 6AL-4V TITANIUM
⬢	180 GR. HEX	LOW	.060 6AL-4V TITANIUM
●	180 GR. HEX	HIGH	.090 2024-T3 ALUMINUM
▲	180 GR. HEX	LOW	.090 2024-T3 ALUMINUM

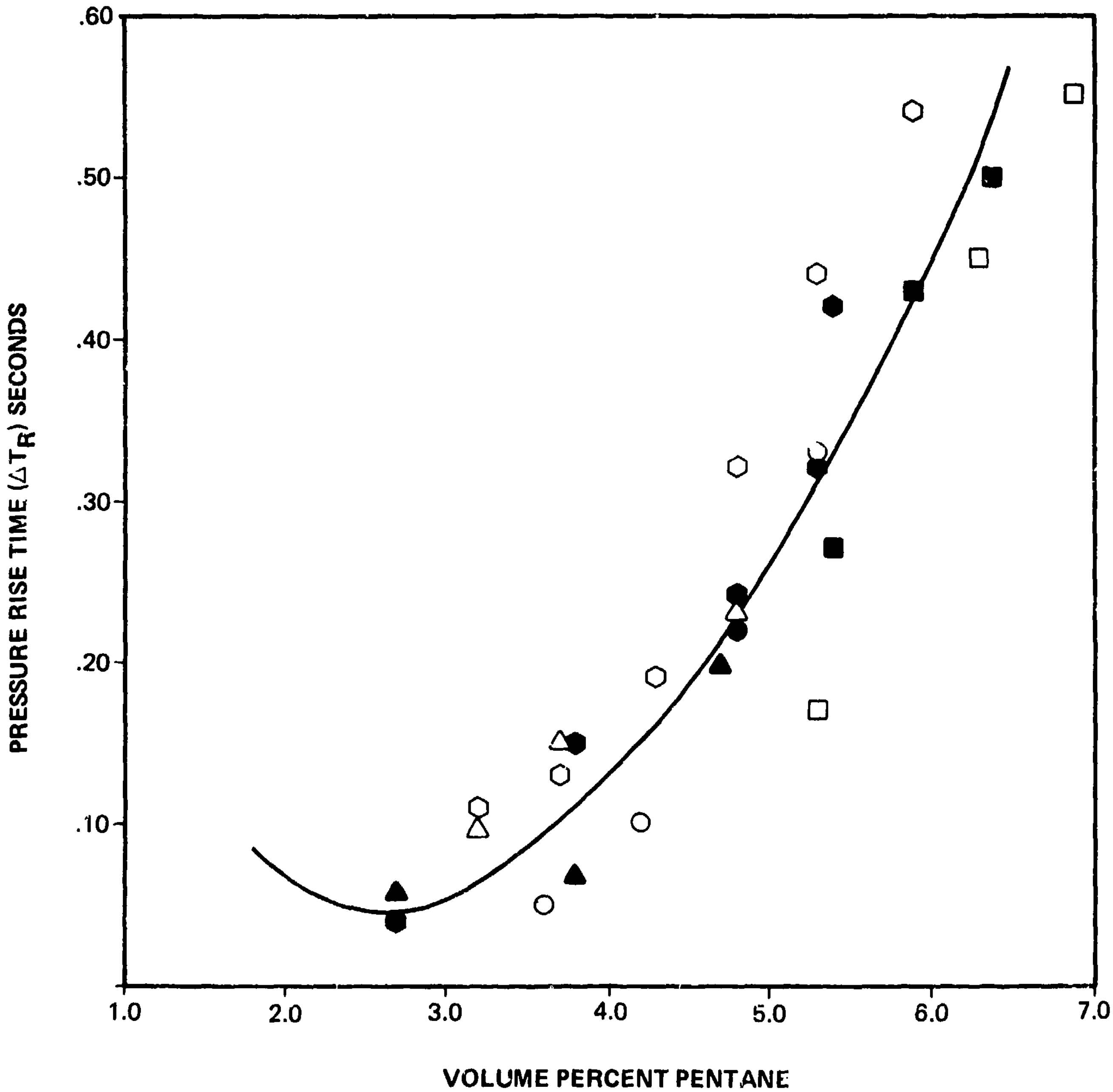
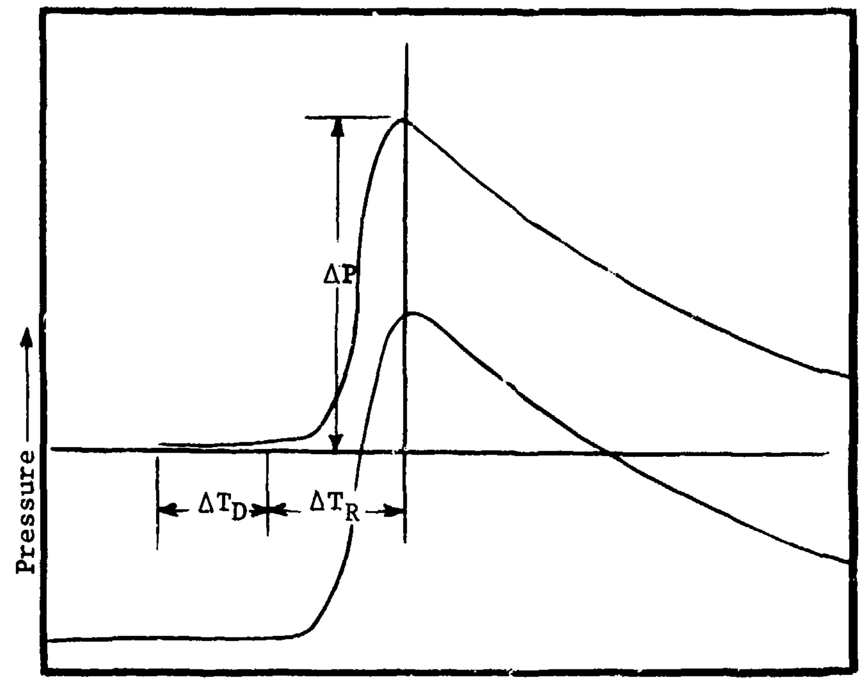
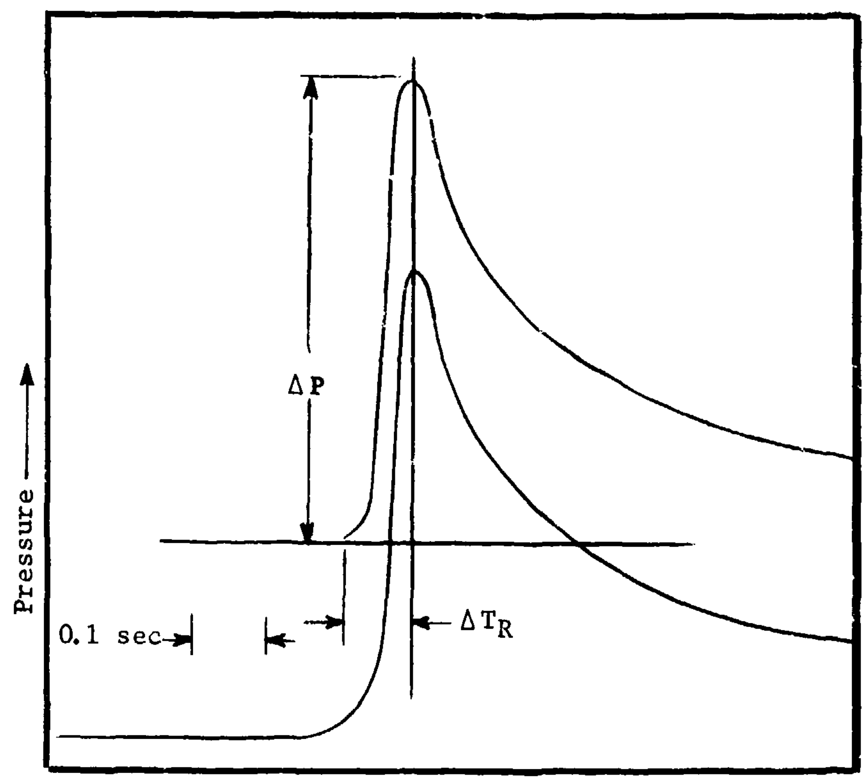


FIGURE 12. AVERAGE TIME TO PEAK OVERPRESSURE VS PERCENT PENTANE.



Delayed Ignition Pressure Trace



Zero-Delay Ignition Pressure Trace

Figure 13. Typical Oscillograph Pressure Data

CONCLUSIONS

The most important parameter affecting P_e is the volume percent fuel vapor. This variable has a greater effect on P_e than the fragment size, type, velocity, entrance plate materials and thicknesses, obliquity and others. Therefore, in choosing values of P_e to be utilized in a vulnerability analysis, the analyzer should attempt to assess the fuel tank ullage conditions at the time of impact. Unfortunately, this is a very difficult task, and there is not sufficient data to determine these conditions. Work is now in progress to construct a model of the fuel tank ullage environment in order to predict fuel vapor concentrations. However, at this time only a very rudimentary model exists.

The most important parameters affecting the fuel vapor concentration in the ullage of a fuel tank are the vapor pressure and temperature of the liquid fuel. These two factors determine the fuel vapor concentration within the tank under well mixed and equilibrium conditions. The fuel vapor pressure depends upon the type of fuel. However, the fuel vapor pressure for a given type of fuel (e.g., JP-4) will vary to some extent and may decrease if the fuel becomes "weathered" (i.e., loses part of the higher volatility components). According to fuel specifications, JP-4 must have a vapor pressure of between two and three psi at 100°F to be acceptable. The vapor pressure of the fuel will exponentially increase as the temperature increases. Therefore, if the vapor pressure of a given sample of fuel is known as a function of temperature, the fuel vapor concentration in the fuel tank can be accurately predicted under well mixed (homogeneous) and equilibrium conditions.

The equilibrium condition implies that the partial pressure of the fuel vapor throughout the ullage is equal to the vapor pressure of the liquid fuel (i.e., a saturated vapor). The fuel tank environment continually strives to achieve this condition of equilibrium. As fuel is withdrawn and replaced by air, the partial pressure of the fuel vapors in the ullage decreases, and the liquid fuel begins to evaporate to increase the partial pressure of fuel vapor and drive the system toward equilibrium. The rate of evaporation is proportional to the difference between the vapor pressure of the fuel at the existing temperature and the partial pressure of fuel vapors in the ullage. On the other hand, if the liquid fuel temperature decreases, the vapor pressure of the liquid fuel becomes less than the partial pressure of the fuel vapors in the ullage. If this occurs, the fuel vapors will begin to condense on the cooler liquid surface and thereby reduce the partial pressure of fuel vapors in the ullage. If the fuel tank walls become cooler than the liquid fuel, the fuel vapors will condense on those walls and the warmer liquid fuel will begin to evaporate to replenish the fuel vapor concentration. This could result in a steady-state, nonhomogeneous situation where the average fuel vapor concentration within the ullage is maintained at some value below equilibrium. Also, if the fuel tank remains quiescent during evaporation of the liquid fuel, a nonhomogeneous condition (a fuel vapor concentration gradient), can occur within the ullage. This is commonly referred to as "stratification."

Motion of the fuel within the tank will tend to drive the system toward equilibrium by mixing the ullage gases and increasing vaporization of the liquid fuel. Changes in altitude can cause great changes in the ratio of fuel vapors to air. During an ascent, large quantities of fuel vapors are expelled from the tank as the internal and external pressures equalize. During an ascent or descent, the quantity of air available to mix with the fuel vapors changes appreciably, thereby altering the fuel vapor/air ratio. Withdrawal or replenishment of the liquid fuel similarly expels fuel vapors from the tank and/or changes the quantity of air by changing the size of the ullage. Other factors can also affect the fuel vapor partial pressure and the fuel/air ratio. The fact that nonequilibrium mixtures often exist in fuel tanks was pointed out in 1948,[5] and Reference [10] contains an excellent discussion of factors which cause nonequilibrium conditions to exist in aircraft fuel tanks.

In order for a fuel tank ullage to be ignited, a sufficient ignition source must be present, and a flammable fuel/air mixture must exist in the vicinity of that ignition source. The energy of the ignition source required to ignite the vapor/air mixture is highly dependent on the fuel/air ratio (which may be stated in terms of volume percent fuel vapor). Even though a fuel vapor/air mixture is flammable, it may not be ignitable for a given ignition source energy. As the fuel vapor concentration increases or decreases from the most easily ignited mixtures, the ignition energy required increases very rapidly. This is described in detail in Reference 11. The JP-4 vapor concentrations in air at 14.7 psia that will support combustion range from 1.5 to 7.8% by volume. Under equilibrium conditions (saturated vapor/air mixtures, this corresponds to liquid fuel temperatures between about -10°F to 50°F[11] or -18°F to 52°F.[12] These temperature limits of flammability will vary somewhat due to variations in the vapor pressure of different samples of JP-4; they will decrease and will approach each other as the altitude increases. Some attempts to establish values of P_e have consisted simply of an assumption that $P_e=1$ whenever the liquid fuel temperatures were within these flammability limits at the altitude of interest. This assumption is unrealistic because it neglects the occurrence of nonhomogeneous and nonequilibrium (unsaturated vapor) conditions that can exist within the fuel tank, as well as the ignitability (rather than flammability) of the vapors. Many investigators have recognized that equilibrium conditions cannot be relied upon in predicting the occurrence of flammable vapor/air mixtures in a fuel tank.[13, 14, 15, 16] Reference 16 presents test data showing ignition of JP-4 at temperatures as high as 130°F under nonequilibrium conditions. Finally, even though the temperature of the liquid fuel may lie below the lower flammability limit, fuel tank explosions can occur. This is due to the formation of flammable fuel mists or foam within the fuel tank during flight and/or the spray thrown up from the liquid fuel when a projectile passes through the liquid and into the ullage. It has been shown[3,14,16,17] that these fine fuel mists or sprays can be ignited by incendiary projectiles and spark ignition sources.

The data shown in Figures 7 through 10 relates P_e to the volume percent pentane. This can be related to volume percent JP-4 vapors, as has been done in Section V of this report. Knowing the vapor pressure of the fuel, the volume percent JP-4 vapor in the ullage can be related to the fuel tank temperature and pressure (altitude) if equilibrium (saturated vapor) and homogeneous (well mixed) conditions are assumed. Therefore, if the fuel tank temperatures and altitude are known as a function of time during a particular mission of an aircraft, a graph of P_e versus time into the mission can be constructed. Although each of these steps involves some inaccuracy or imprecision, the greatest inaccuracies are introduced when the conditions of homogeneity and equilibrium are assumed. Exploratory techniques to reduce this inaccuracy are available, such as the fuel tank modeling program described in Reference 18.

Based upon the results of the uninerted ullage tests and other available data, the following conclusions regarding P_e can be made:

1. The test parameter having the greatest effect on P_e is the volume percent fuel vapor.
2. Titanium entrance plates resulted in higher values of P_e than aluminum entrance plates.
3. Except for the intermediate velocity tests performed at the 90 grain hexagonal fragment/aluminum entrance plate test condition, P_e generally increases with increasing fragment velocity.
4. Fragment velocities greater than the 5,750 ft/sec velocity tested will probably not substantially increase the fuel vapor concentration ignitability limit (the fuel vapor concentration where P_e falls to zero), because these mixtures are approaching the rich flammability limit.
5. The peak combustion overpressures attained in these tests varied from approximately 120 psi to 40 psi as the pentane concentration was increased.
6. The diamond shaped fragment appeared to be slightly less likely to produce explosions than the hexagonal fragment of the same mass. This difference may be statistically insignificant, and/or insignificant with regard to the intended use of this data in a vulnerability analysis.
7. The few tests performed with painted entrance plates show no indication that the paint had any effect on P_e or the impact flash within the tank. Although these few tests cannot be considered to be conclusive, in the absence of additional information it is recommended that the effect of paint be neglected.
8. Increasing the thickness of the entrance plate material may serve to increase P_e by increasing the intensity, duration, or size of the

impact flash and the sparks. Although this was not observed on the high speed films, the values of P_e did increase when the material thickness was increased. Increasing the angle of obliquity should have an effect on P_e that is similar to increasing material thickness. However, if the material thickness or angle of obliquity becomes great enough to cause most of the impact flash to occur on the front side of the entrance material, P_e would be expected to decrease, Since most aircraft fuel tank walls are relatively thin, this may not be of too great a concern.

9. Decreasing the pressure (increasing altitude) causes the energy required to ignite specific fuel vapor concentrations to increase.(9) Therefore, at higher altitudes, the values of P_e shown in Figures 7 through 10 would be expected to decrease. However, this effect may not be significant.

10. Unless the fragment produces very large holes in the fuel tank, airflow due to motion of the aircraft probably has very little effect on P_e. The initiation of combustion within the tank usually occurs too rapidly for a significant amount of air to enter the fuel tank and change the fuel/air ratio.

11. The fragment rapidly decelerates within the liquid fuel. Also, no impact flash can occur within the liquid fuel. If the fragment passes through more than a few inches of fuel before entering the ullage, it will probably not retain sufficient energy to cause an impact flash upon exiting the tank. Therefore, it is recommended that very low values of P_e be applied when this situation occurs. The liquid fuel can similarly quench an incendiary projectile which passes through it and into the ullage. Reference 16 shows that increasing the depth of fuel beyond 12 inches reduced P_e for a 0.50 caliber armor-piercing incendiary (API) projectile passing through the liquid and into the ullage under the conditions of those tests.

Section IV
INERTED ULLAGE TESTS

FUEL TANK NITROGEN INERTING

The purpose of fuel tank nitrogen inerting is to prevent combustion overpressures from occurring in the ullage spaces of aircraft fuel tanks. This is accomplished by diluting the gas mixture within the ullage with nitrogen to the point where the oxygen concentration is too low for significant combustion overpressures to occur. The nitrogen required to accomplish this is carried on the aircraft in cryogenic dewars and is vented into the fuel tanks as required to maintain fuel tank pressure, or as a purge gas (constant flow system). Unsuccessful attempts have been made to use engine exhaust gas and the combustion products of burning fuel to inert fuel tanks. The Fire Protection Branch of the Aero Propulsion Laboratory is currently investigating and/or developing other techniques to generate inert gas onboard aircraft.

The quantity of nitrogen required to inert the fuel tanks of an aircraft is, of course, the primary factor to be considered when designing an inerting system. The minimum oxygen concentration that will allow flame propagation within a fuel tank is about 11.5% by volume when nitrogen is used for inerting at sea level pressure.[11] The minimum oxygen concentration required for flame propagation increases slightly with increasing altitude and decreases slightly with increasing temperature. Reference 11 presents an equation for calculating the effect of temperature and presents test data demonstrating the effect of altitude. Other inerting gases have different minimum oxygen concentrations which will allow a flame to propagate. For example, carbon dioxide prevents flame propagation below 14% oxygen by volume.[11] All the above cited minimum oxygen concentrations apply to JP-4 vapor, air, and nitrogen or carbon dioxide gas mixtures. Most hydrocarbons, including pentane, require similar quantities of inert gases for inerting.

The fuel vapor concentrations that will allow flame propagation at or near these minimum oxygen concentration values span a very narrow range of fuel vapor concentrations. This provides an additional safety factor in that the probability of the occurrence of a flammable fuel vapor concentration at these low oxygen concentrations is relatively small.

Other investigators have reported maximum "safe" oxygen concentrations ranging from about 9.[illegible]% to 12% by volume. Reference 19 contains a compilation of these results. The cause of these variations in maximum "safe" oxygen concentrations is the difference in the ignition sources used and the criteria for establishing "safe" oxygen concentrations. The effect of the ignition source can be considerable and is discussed in detail in Reference 20. In some cases, investigators were determining the ignitability rather than the flammability of these low oxygen concentration mixtures. The ignition sources may not have been sufficient to ignite some mixtures, even though these mixtures may have been flammable. On the other hand, some investigators [21] considered any appearance of flame to constitute an "unsafe" situation, whether this flame propagates throughout the mixture or not. This caused Stewart and Starkman[21] to conclude that about 9.5% oxygen by volume represented the maximum "safe" oxygen concentration (maximum oxygen concentration above which combustion can occur).

In order to better define the maximum safe oxygen concentration for fuel tank inerting, the Fire Protection Branch of the Aero Propulsion Laboratory has been performing tests at these low oxygen concentrations. The results of these tests[1,20] will be briefly summarized here.

Whenever a large enough ignition source is available, some combustion will occur if fuel and an oxidizer (air) are present. The combustion may not be able to sustain itself in the absence of the ignition source or propagate through the mixture, but combustion will occur at least in the vicinity of the ignition source. If the ignition source is an incendiary projectile, the incendiary flash can locally heat a "nonflammable" fuel/air/nitrogen mixture to the point where some of the fuel and oxygen molecules react, thereby releasing additional heat. The impact flash and hot incandescent particles produced by the impact of a fragment on a fuel tank should have a similar although smaller, effect. The amount of combustion that occurs will depend upon the size, intensity, and duration of the ignition source, and the distance that a flame can propagate from the ignition source. Flammable gas mixtures are those in which a flame can propagate indefinitely. Propagation of a few inches to a foot or more is possible in "nonflammable" mixtures, especially with a large and powerful ignition source. The distance that a flame can propagate from an ignition source and through a nonflammable mixture decreases with the oxygen concentration. Some combustion occurred in all tests performed and described in References 1 and 20, even at oxygen concentrations as low as 7.5%. Therefore, it is concluded that no unique oxygen concentration exists below which some combustion cannot occur.

The heat generated by the limited combustion of a portion of the fuel vapors will manifest itself as a rise in pressure within the fuel tank. The heat produced by an incendiary projectile or a fragment impact has a similar effect. For example, it was found that the pressure rise caused by a 0.50 caliber API in a 100 gallon tank filled with air was one to two psi. The pressure rise due to the heat generated by the incendiary flash or fireball is inversely related to the ullage volume of the test tank. That is,

$$\Delta P = \frac{PQ}{VC}$$

where

ΔP = pressure rise

R = gas constant

Q = heat input

V = volume of tank

C = specific heat

Thus, decreasing the volume of the tank results in a correspondingly higher pressure rise. This has been observed in other tests performed by the Aero Propulsion Laboratory. Since the combustion that occurs in an "inerted" gas mixture is limited to the vicinity of the ignition source, it would seem reasonable to assume that the amount of gas that combusts, and therefore the amount of heat generated, would be relatively independent of the fuel tank volume. Therefore, the inverse relationship between pressure rise and the fuel tank volume should also apply to the pressure rise occurring in fuel tanks containing low oxygen concentration fuel vapor/air/nitrogen mixtures. Part of the objective of the uninerted ullage tests performed in this program was to evaluate the effect of fuel tank volume on the combustion overpressures occurring. For this reason, an 800 gallon test tank was used and the results compared to the previous AFAPL test results obtained in a 100 gallon test tank. These previous tests were performed with pentane/air/nitrogen mixtures at 10% oxygen by volume, and a portion of the results are shown in Figure 14. The ignition source was a device (incendiary ignitor) which duplicated the incendiary flash or fireball produced by a properly functioning 0.50 caliber armor-piercing incendiary projectile. This device is described in detail in Reference 1. It is important to note that the ignitor does not produce projectile entrance and exit holes in the tank.

Examination of Figure 14 will reveal that the 0.50 caliber API produced very low overpressures as compared to those produced by the ignitor. This has been attributed to the effect of venting gases (pressure relief) through the holes created by the projectile in passing through the tank. The amount of pressure relief that occurs is directly proportional to the size of these holes and the time available for this pressure relief to occur. The time available for pressure relief is the time required for the reaction to attain peak combustion overpressure (i.e., Δt_R). For the 10% oxygen concentration mixtures, Δt_R was very often greater than one second and averaged nearly one second. Thus, the time available for pressure relief was relatively large and the peak combustion overpressures were consequently reduced with the 50 API as compared to the ignitor. Tests performed with a near stoichiometric pentane and air (uninerted) mixture resulted in very short pressure rise times (30 to 60 msec) under the same test conditions. No difference in the peak combustion overpressures attained with the ignitor and the 50 API projectiles was noted in those tests.[1] In order to verify the effect of pressure relief on slowly reacting mixtures, additional tests were performed at the 10% oxygen level with the incendiary ignitor and simulated projectile entrance and exit holes (vents). Although these holes were much smaller than those produced by a 0.50 caliber API projectile, the results (see Figure 14) did show a significant decrease in the

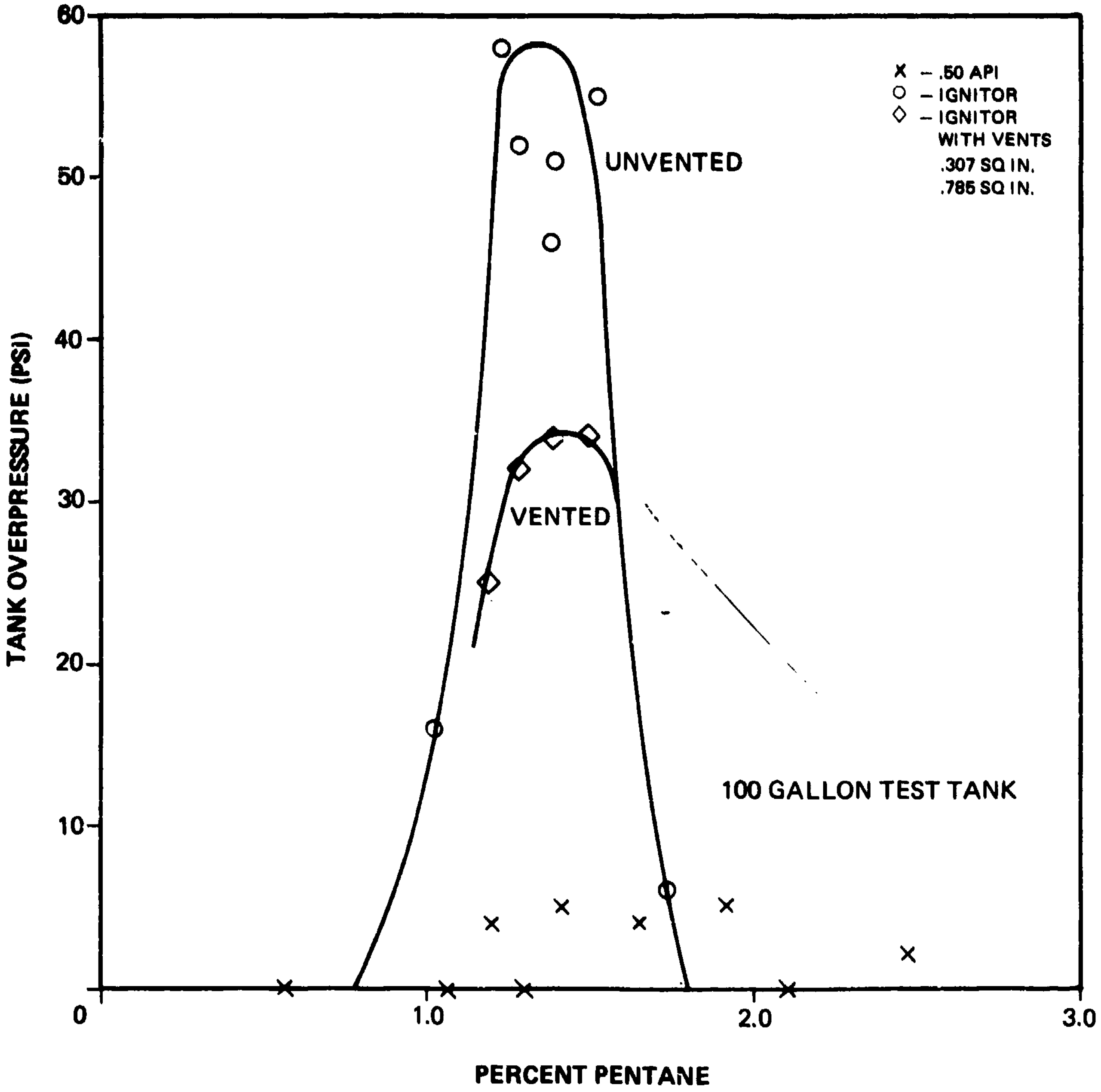


FIGURE 14. TANK OVERPRESSURE VS PERCENT PENTANE AT 10 ± .2% OXYGEN (REF. 24).

peak overpressures. The holes produced by the 50 API projectile had a total vent area averaging about three times that of the simulated vents. Also, about 90% of the vent area of the holes produced in the test tank entrance and exit plates consisted of the exit plate holes' vent area. It was concluded that pressure relief through the holes created by a projectile passing through a tank can significantly reduce the peak combustion overpressure for slowly reacting mixtures, such as those of a 10% oxygen, fuel vapor/air/nitrogen mixture. Also, if a projectile should fail to produce appreciable size holes in the fuel tank, due to failure of the projectile to exit or exit below the fuel level, the overpressures would more closely resemble those attained in the unvented ignitor tests (Figure 14). However, the effect of fuel tank ullage volume could greatly affect the maximum overpressure.

TEST CONDITIONS

The objective of these inerted ullage tests was to evaluate the effectiveness of the level of nitrogen inerting (maximum 10% oxygen by volume) that had been proposed for certain aircraft fuel tanks. Specifically, this consisted of the following:

- o An evaluation of the fuel tank ullage volume versus ΔP relationship for nonflammable gas mixtures that was discussed in the previous section.
- o Assurance that the combustion reaction could not propagate any great distance from the ignition source at 10% oxygen by volume.
- o An evaluation of the effects of different threats than those tested in Reference 1.

In order to evaluate the fuel tank ullage volume versus ΔP relationship, an 800 gallon test tank was utilized, and the results were compared with those previously obtained in the 100 gallon tank. To ensure that the combustion reaction could not propagate any great distance from the ignition source, a 20 inch diameter tube was mounted extending approximately 4.5 feet radially from the main tank (see Figure 16). This extension section had a viewing port through which the appearance of any flame could be observed and photographically recorded.

The primary variable in these tests was the threat. Tests were performed with the 180 grain hexagonal fragment, 0.50 caliber armor-piercing incendiary projectiles, the incendiary ignitor, two different 14.5 mm API projectiles, and a 23 mm high explosion incendiary (HEI) projectile. The entrance plate materials and thicknesses were varied to provide proper functioning of the larger threats. A 0.060 in. 6Al-4V titanium entrance plate was used in the fragment tests. The pentane vapor concentration was varied slightly and the oxygen concentration was maintained at 10% by volume. The gas mixture was sampled before each of these tests, and the oxygen concentration was verified. All tests were performed at 16.2 psia. The gas mixture was well mixed by two fans located within the test tank.

The test tank was an approximately 800 gallon, cylindrical test article with a 20 inch diameter cylindrical section extending radially from the main tank. The test tank is shown schematically in Figure 15, and a photograph of this test article is shown in Figure 16. The diameter of the test tank was five feet, and the axial length was five feet. The exit plates used in all the inerted ullage tests were 0.090 in. 2024-T3 aluminum sheet. The entrance plate size and the entrance plate attachment and sealing assembly were identical to that of the void area and uninerted ullage tests. In order to prevent severe damage to the rear flange of the test tank during the 23 mm HEI projectile tests, one tier of 4 in. × 4 in. wood pieces were stacked at the rear of the tank. These wood pieces did not cover the 20 inch diameter exit hole over which the exit plate was attached.

Two strain gage pressure transducers and a thermocouple were used to obtain pressure versus time traces and initial temperature. Also, two high speed motion picture cameras (7,000 frames/sec) were used to view the interior of the tank during these tests. One camera was mounted in such a manner that it viewed the interior of the main tank. The other camera was mounted on the cylindrical extension section, looking radially into the extension.

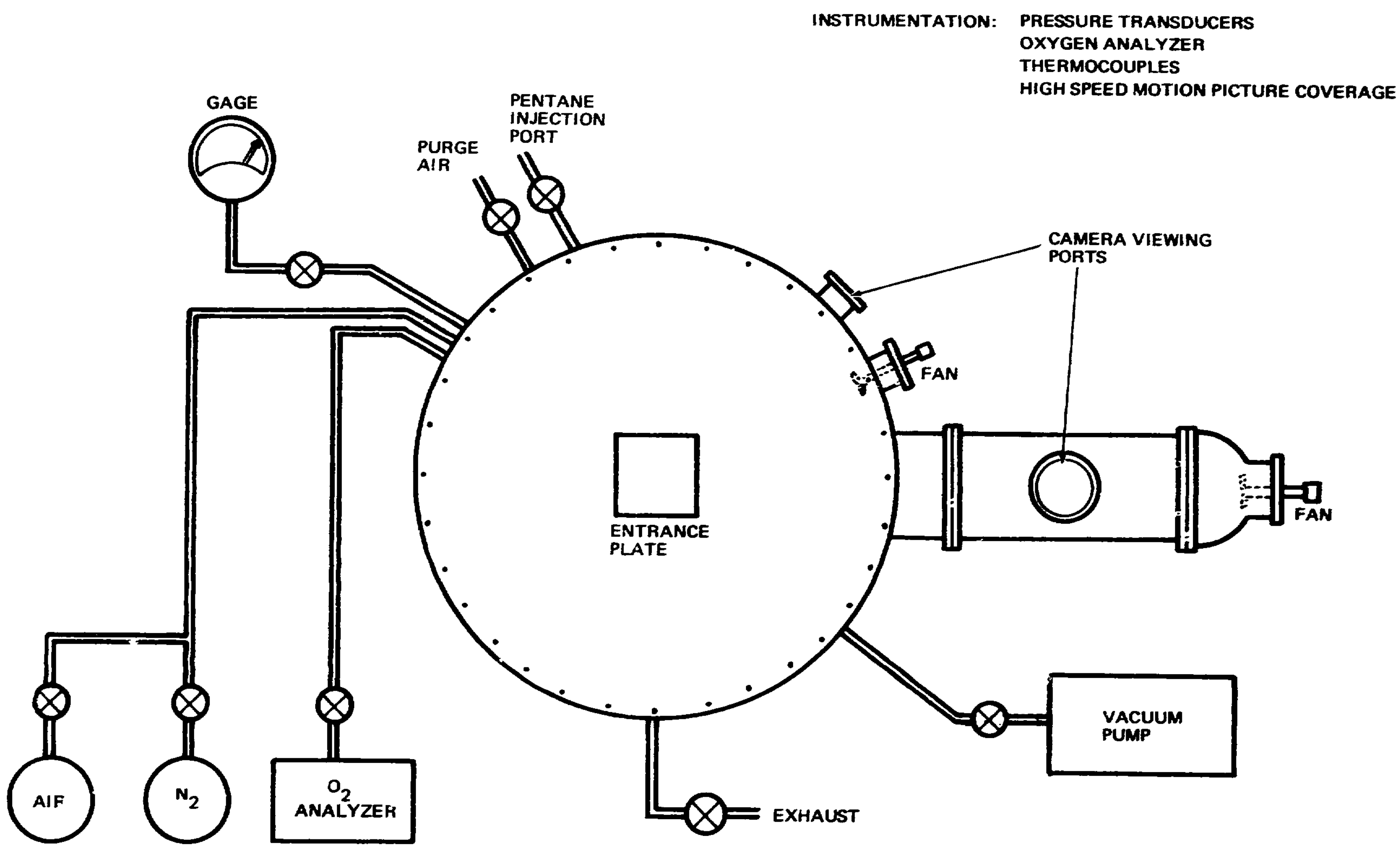


FIGURE 15. INERTED ULLAGE TEST SETUP.

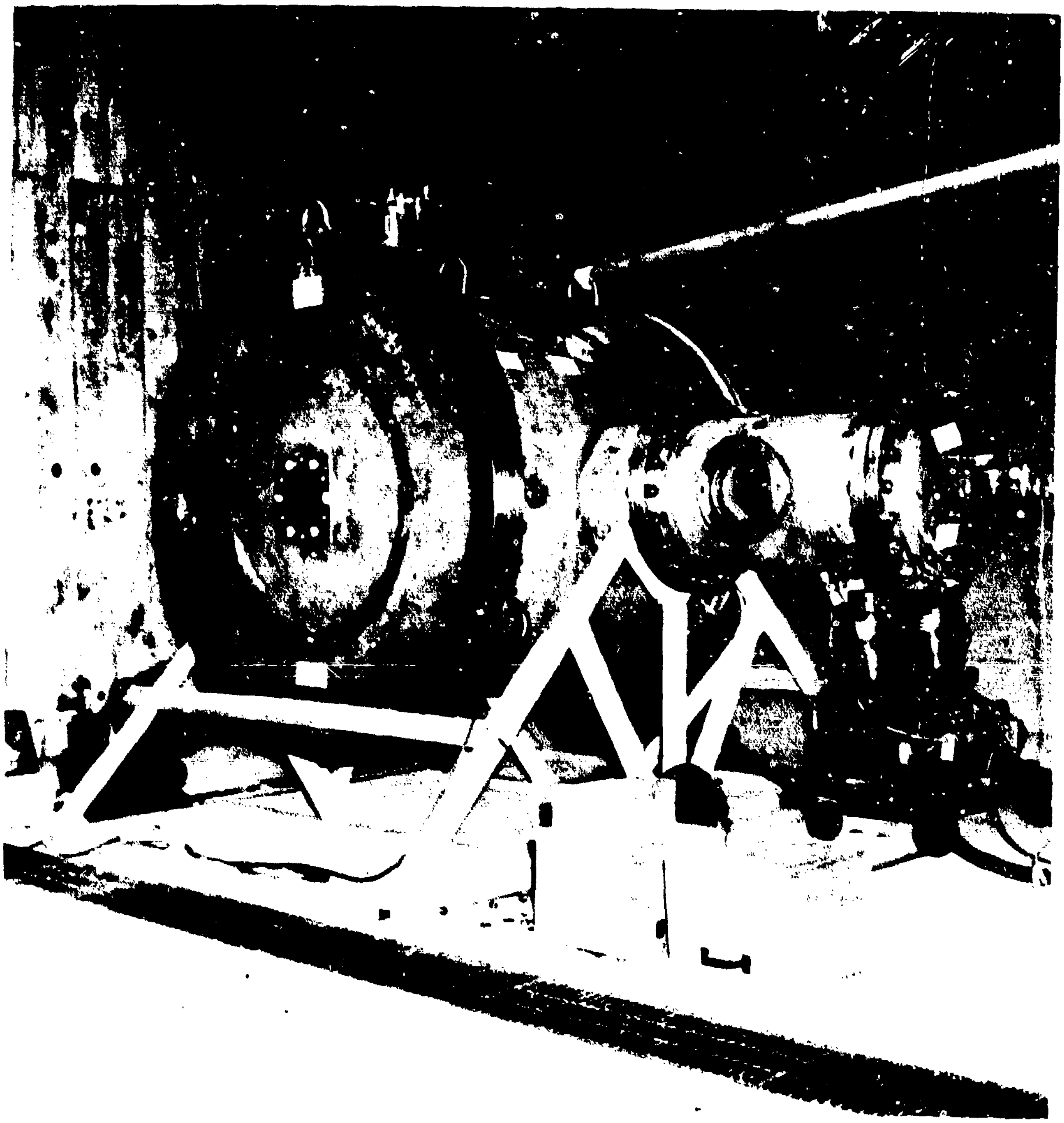


FIGURE 16. SIMULATOR TANK.

INERTED ULLAGE TEST PROCEDURE

The following is the test procedure utilized in these tests.

1. Vacuum test article to less than 2 psia.
2. When vacuum pumps are shut off and pressure has stabilized, record test number, time, date, and pressure reading.
3. Calculate volume of liquid pentane required to produce desired fuel/air ratio.
4. With circulation fans running, inject pentane into test article.
5. Record pressure in test article after adding pentane.
6. Pressurize test article with bottled air to the pressure required to produce a 10% oxygen concentration at 16.5 psia.
7. Pressurize test article with bottled nitrogen to 16.5 psia.
8. Turn on switch to actuate analyzer pump and sensor.
9. When analyzer reading is stable, record value. Oxygen concentration should be between 10.0 and 10.2% by volume.
10. Bleed gas mixture pressure to 16.20 psia.
11. Close manual valves.
12. Instruct gun crew to load and prepare weapon.
13. When countdown is initiated, shut off mixing fans and start pressure oscillograph.
14. When range is clear, change entrance and exit plates and thoroughly purge tank with shop air.

INERTED ULLAGE TEST DATA AND RESULTS

A compilation of the data obtained in these inerted ullage tests is shown in Table III. The only ignition source that was able to produce any significant combustion overpressure in the test tank was the incendiary ignitor (tests 10-16). The inability of the other threats to produce combustion overpressures is attributed to the effect of pressure relief through the entrance and exit holes caused by those threats. Note that the times required to attain the peak combustion overpressures for the ignitor tests were relatively long. The pressure versus time traces for the projectile threats showed no

TABLE III

INERTED ULLAGE TESTS								
TEST NO.	VOLUME PERCENT PENTANE	THREAT	ENTRANCE PLATE	VELOCITY	EXP	ΔP (PSI)	ΔT_R (SEC)	REMARKS
1	1.25	14.5mm B541 API	.250 2024-T3 Al	Unknown	No	0		
2	1.40	"	"	Unknown	No	0		
3	1.25	14.5mm B-32 API	"	3189 FPS	No	0		
4	2.62	"	"	3200 FPS (est)	Yes	Unknown	Unknown	21% Oxygen Test Shot Press Transducer Malfunc.
5	1.25	"	.188 2024-T3 Al	3220 FPS	No	0		
6	1.40	"	"	3144 FPS	No	0		
7	1.30	"	.375 2024-T3 Al	3246 FPS	No	0		
8	1.28	.50 cal APIT	.250 2024-T3 Al	Unknown	No	0		
9	1.40	.50 cal API	.188 2024-T3 Al	2877 FPS	No	0		
10	1.30	Incendiary igniter	—	—	Yes	9.4	2.2	
11	1.50	"	—	—	Yes	6.7	1.9	
12	1.70	"	—	—	Yes	1.1	0.8	
13	1.1	"	—	—	No	0		
14	1.4	"	—	—	No	0		
15	1.4	"	—	—	Yes	6.24	2.0	
16	1.2	"	—	—	Yes	Unknown	Unknown	Visicorder Failure
17	1.3	14.5mm B-32 Type BZ API	.500 2024-T3 Al	Unknown	No	0		
18	1.3	"	"	Unknown	No	0		
19	1.4	"	"	Unknown	No	0		
20	1.4	14.5mm B-32 Type BZ APIT	"	Unknown	No	0		

TABLE III (continued)

INERTED ULLAGE TESTS								
TEST NO.	VOLUME PERCENT PENTANE	THREAT	ENTRANCE PLATE	VELOCITY	EXP	ΔP (PSI)	ΔT_R (SEC)	REMARKS
21	1.3	180 Grain Hex Frag	.060 6A1-4V Ti	Unknown	No	0		
22	1.3	180 Grain Hex Frag	.060 6A1-4V Ti	5555 FPS	No	0		
23	1.3	180 Grain Hex Frag	.060 6A1-4V Ti	5649 FPS	No	0		
24	1.3	180 Grain Hex Frag	.060 6A1-4V Ti	5865 FPS	No	0		
25	1.3	23mm HEI	.032 2024-T3 Al	Unknown	No	0		
26	1.3	23mm HEI	"	Unknown	No	0		

discernible rise. Even a pressure rise as low as 0.5 psi would have been noticeable, but was not observed. The response time of the pressure recording equipment was not great enough to record the relatively rapid and transient blast overpressures that may have occurred with the 23 mm HEI projectiles.

The purpose of the cylindrical extension section was to provide an area that would be relatively undisturbed by the ignition source and could therefore be used to determine if flame propagation can occur in that gas mixture independent of the ignition source. The high speed camera looking radially into this extension section was capable of recording any flame propagation. Combustion was never observed in the extension section.

The initial pressure within the tank was 16.2 psia. The previous inerting work[1] (see Figure 14) was performed at ambient pressure, approximately 14.4 psia. This increase in initial pressure should cause the overpressures to be proportionally higher. Test No. 10 resulted in the highest overpressure observed, 9.4 psi. Multiplying this value by the ratio of initial pressures, 14.4:16.2, results in a "corrected" value of 8.35 psi. The highest overpressure attained in the 100 gallon test tank (Figure 14) was 58 psia. The only difference between these tests was the tank volume and initial pressure. The ratio of the "corrected" peak combustion overpressure in the 800 gallon tank to the peak combustion overpressure attained in the 100 gallon tank is approximately 1/7. The ratio of the volumes of these two test articles is 8. Thus, the linear inverse dependence of the peak combustion overpressure to the test tank volume ($\Delta P = RQ/VC$), discussed previously, appears reasonably accurate, though not exact.

INERTED ULLAGE TEST CONCLUSIONS

The results of these inerted ullage tests are in agreement with the results of the previous and more extensive AFAPL inerting tests.[1] As a result of both of these programs it can be concluded that the level of nitrogen inerting evaluated (10% oxygen by volume) will effectively prevent significant combustion overpressures from occurring in the fuel tanks in most instances. In order for the overpressures to be severe enough to do damage to the fuel tank, the following variables must simultaneously be in a worst case condition:

- o Fuel tank ullage volume must be small.
- o Available pressure relief venting area must be small.
- o Oxygen concentration must be high (near 10%).
- o The fuel vapor concentration must be correct.

The effect of the fuel tank ullage volume on the peak combustion overpressure can be estimated by extrapolating the test data obtained in this program and, to a greater extent, the data reported in Reference 1. This can be done by assuming that the product of the peak combustion overpressure and the fuel tank volume remains constant. This is a worst case estimation in that it assumes that no pressure relief occurs and the fuel vapor concentration is at a worst case level. Also, the oxygen concentration must be at the same level as it was in the test data used in this extrapolation.

The effect of pressure relief can be significant, as demonstrated by a comparison of the ignitor and 0.50 caliber API projectile tests shown in Figure 14. Pressure relief occurs as a result of the holes produced by the projectile or fragment, and may also occur as a result of fuel tank vents, particularly if the aircraft has an "open vent" system. If the effective venting area is small, due to failure of the projectile to exit or exit below the fuel level, the effect of pressure relief may be minimal and approach the worst case situation of no vents.

The effect of oxygen concentration on the peak combustion overpressures can also be significant. Reducing the oxygen concentration from 10% to about 7.5% decreased the maximum overpressure from 58 psi to 10 psi.(1) These tests were performed under worst case conditions of fuel vapor concentration, with the ignitor in a 100 gallon tank and at about 14.4 psia. Extensive data regarding the combustion overpressures occurring at other oxygen concentrations is shown in References 1 and 20.

The fuel vapor concentrations that are required to produce significant overpressures at these low oxygen concentrations are very limited. Figure 14 demonstrates the relatively narrow fuel vapor concentrations that are required at 10% oxygen. The range of these fuel vapor concentrations decreases with oxygen concentration.

The probability of all of the above discussed conditions occurring simultaneously is quite small. Therefore, the effectiveness of the 10% oxygen level of nitrogen inerting is considered to be very good.

Section V

PENTANE/JP-4 COMBUSTION COMPARISON TESTS

INTRODUCTION

The uninerted and inerted ullage tests reported in Sections III and IV, respectively, of this report were performed using pentane as the fuel. The use of pentane in place of JP-4 reduces the realism and degree of simulation attained in these tests. However, due to the very great difficulty and inaccuracy involved in controlling the fuel vapor concentration with JP-4, and due to the much greater test time that would be required, pentane was used. In order to justify the use of pentane instead of JP-4, a series of tests was performed to compare the pertinent combustion properties of these two fuels.

The use of a pure and single (neat) hydrocarbon fuel in this type of test program is not new or unique to this program. Most of the basic combustion data[9] has been obtained with neat hydrocarbon fuels. Also, almost all of the testing that has been done to evaluate and qualify the fuel tank flame arrestor materials and voiding (penalty-reduction) techniques has been done with neat hydrocarbon fuels. Even the qualification tests of the advanced explosion suppression flame arrestor voiding concept for the F-15 wing tanks were performed with a neat hydrocarbon fuel (propane). Reference 22 is a report of one of the fuel tank flame arrestor voiding concept development efforts and contains a brief discussion of the use, and the reasons for the use, of a neat hydrocarbon rather than JP-4.

JP-4 is a mixture of more than 1,000 different hydrocarbons. Appendix II is a list of 75 of the major components of a sample of the JP-4 fuel used in these tests. This data was obtained via gas chromatography. The components are listed in order of increasing molecular weights, and the components which can be identified are also shown. The mass percentages of each of the components are also presented. These are the mass percentages of each component in a sample of the liquid fuel, and they are not the same as the volume or mole percentages of those components in the vapors. Since the lower molecular weight components have a much higher volatility (vapor pressure), they constitute a much greater percentage of the vapors. Thus, even though the average molecular weight of liquid JP-4 is approximately 125, the average molecular weight of JP-4 vapors is approximately 72 at about 70°F. The average molecular weight and the percentages of each constituent of JP-4 vapors vary with temperature. Also, because the vapor pressure of JP-4 is allowed to vary between two and three psi at 100°F according to the fuel specification, considerable variations in the properties of samples of JP-4 can be expected. For example, if this variation in the volatility of JP-4 fuel is applied to the calculation of saturated (equilibrium) vapor concentrations in air, the results are as shown in Figure 17. This figure demonstrates the difference in fuel vapor concentration in the ullage of a fuel tank, under equilibrium conditions and at 16.2 psia, for the highest and lowest volatility JP-4 fuels that are acceptable according to MIL-T-5624H. Furthermore, since the constituents of the vapors of a sample of JP-4 vary with the temperature and fuel volatility, and since these constituents may have different combustion characteristics, the combustion properties of different samples of JP-4 may vary over a wide range.

The use of JP-4 in tests of this type imposes several difficult problems on the performance of these tests. First, very accurate temperature control of the fuel and test article is required. Temperature homogeneity of the liquid fuel, ullage air, and test article is necessary to attain equilibrium. Also, this temperature homogeneity must be maintained for whatever period of time is required for the liquid fuel vapor pressure to come to equilibrium with the partial pressure of fuel vapors in the ullage. Therefore, a well insulated test article and a fuel conditioning system are required. Also, if the partial pressure of air above the fuel is allowed to vary to any great degree from the fuel storage tank to the test article, oxygen and nitrogen will be dissolved into, or released from, the fuel. The fuel preferentially absorbs oxygen and can thereby affect the oxygen concentration in the ullage.

The rate of evaporation of the liquid fuel increases with the surface area of the fuel and the difference between the vapor pressure of the fuel and the partial pressure of fuel vapor in the ullage. Thus, the rate of evaporation

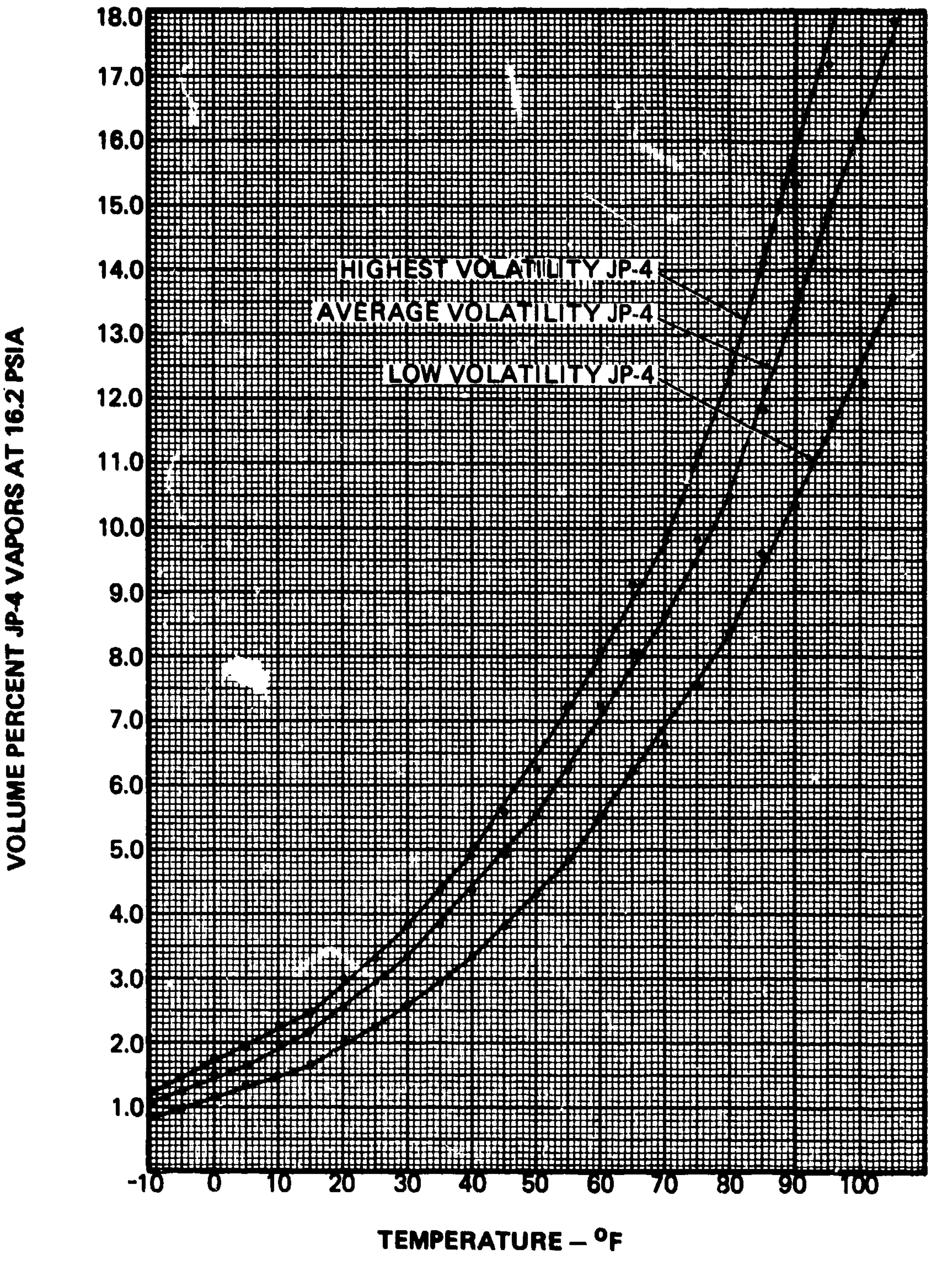


FIGURE 17. PERCENT JP-4 VAPOR VS TEMPERATURE

decreases as the fuel liquid/vapor system approaches equilibrium. The time required for the system to come to equilibrium under quiescent conditions can be very great, often many hours. In order to decrease this time, the system must be agitated. For the JP-4 tests described in this section, a fan was mounted in the test tank to circulate and mix the ullage gases. Since JP-4 vapors contain some large and relatively heavy hydrocarbon molecules, stratification of the fuel vapors can be a problem. The fan prevents this stratification from occurring. However, the fan did not cause rapid enough evaporation of the fuel, and equilibrium was not occurring even after more than an hour. In order to increase the evaporation rate, it was necessary to increase the effective surface area of the liquid fuel. This was accomplished by pumping the liquid fuel from the bottom of the tank and spraying it onto the rotating fan blades. This resulted in the formation of small fuel droplets and also wetted the side of the test tank, thereby providing a much larger liquid fuel surface area. Equilibrium was thus attained in about 15 minutes.

Normal pentane is a pure hydrocarbon with a relatively high vapor pressure (15.57 psi at 100°F as compared to an average of 2.6 psi at 100°F for JP-4). Flammable pentane and air mixtures range from 1.5 to 7.8 volume percent pentane vapors.[9] Because of the high vapor pressure of pentane and the relatively low partial pressures of pentane vapors that are within the flammable region, all of the small amount of liquid pentane injected into the tank will evaporate. Therefore, by controlling the quantity of liquid pentane introduced into the test tank, the desired pentane vapor concentration can be controlled. Thus, the need for accurate and very homogeneous temperature control is eliminated at normal temperatures (above -20°F). The test tank temperature must be included in the calculation of the required quantity of liquid pentane to be injected, but the test tank temperature need not be controlled and has no other effect on the fuel vapor concentration.

Because pentane has such a high vapor pressure, evaporation occurs rapidly. If the test tank is at least partially evacuated, the pentane will evaporate within a minute or two; thus, the spraying of liquid fuel (as with JP-4) within the tank is unnecessary. Also, the pentane vapors exhibit less tendency to stratify than JP-4 vapors. A fan mounted within a test tank eliminates any stratification problems and increases the rate of evaporation of the pentane liquid. Finally, the quantity of pentane liquid required for a test is far less than the quantity of JP-4 required (50 to 150 milliliters versus 90 gallons). Therefore, far less of the flammable fluid is required and the safety of these tests is thereby enhanced.

A comparison of some of the pertinent properties of pentane and JP-4 is shown in Table IV. Although many other neat hydrocarbons could have been used to simulate JP-4 vapors, pentane appears to be an excellent choice, especially since its flammability limits are nearly the same as those of JP-4.

TEST CONDITIONS

The objective of these tests was to compare the combustion effects of JP-4 and pentane vapors in order to verify and/or correlate the results of the uninerted and inerted ullage tests with the actual aircraft fuel. The characteristics of the combustion reactions of the two fuels that were evaluated were:

- peak combustion overpressure
- time required to attain the peak overpressure
- ignitability limits
- fuel vapor concentrations that resulted in the maximum overpressure

The test article used in these tests was a reinforced steel tank having a volume of 90.7 gallons. A schematic of the test apparatus is shown in Figure 18. The tank was equipped with a sampling system, an externally driven fan, a pentane injection port, a fuel circulation and cooling system, fuel inlet, outlet, and circulation lines, a site gage, a pressurization (dry compressed air) line, and a vent line. The ignition source was a spark plug powered by a ten kilovolt transformer of the type used for ignition in fuel oil furnaces. The instrumentation consisted of five type "J" thermocouples for determining test tank internal temperatures and a strain gage pressure transducer and oscillograph to obtain pressure versus time information. The sample bottle was similarly equipped with a spark plug, thermocouple, and

TABLE IV

COMBUSTION PROPERTIES OF JP-4 AND PENTANE

	n-pentane	JP-4
Molecular weight	72.15	approx 125 for liquid approx 72 for vapors at 70°F
Flammability limits in air at one atmosphere (volume percent)	1.5 to 7.8 (Ref 9)	1.3 to 8.0 (Ref 11)
Vapor pressure at 100°F (psi)	15.57	2.0 to 3.0
Minimum oxygen concentration required for flame propagation (volume percent)		
N_2 inerting	12.1	11.5
CO_2 inerting	14.6 (Ref 9)	14.3 (Ref 11)
Maximum burning velocity in air at atmospheric pressure (ft/sec)	approx 1.5	assumed to be approx the same (Ref 11)
Minimum spark ignition energy in air at one atmosphere (millijoules)	0.25 (Ref 11)	approx 0.25 (Ref 11)
Spontaneous ignition temperature (°F)	544-554 (Ref 23)	468 (Ref 23)
Heat of combustion (Btu/lb)	19,499 (lower) (Ref 24)	18,710 (Ref 11)

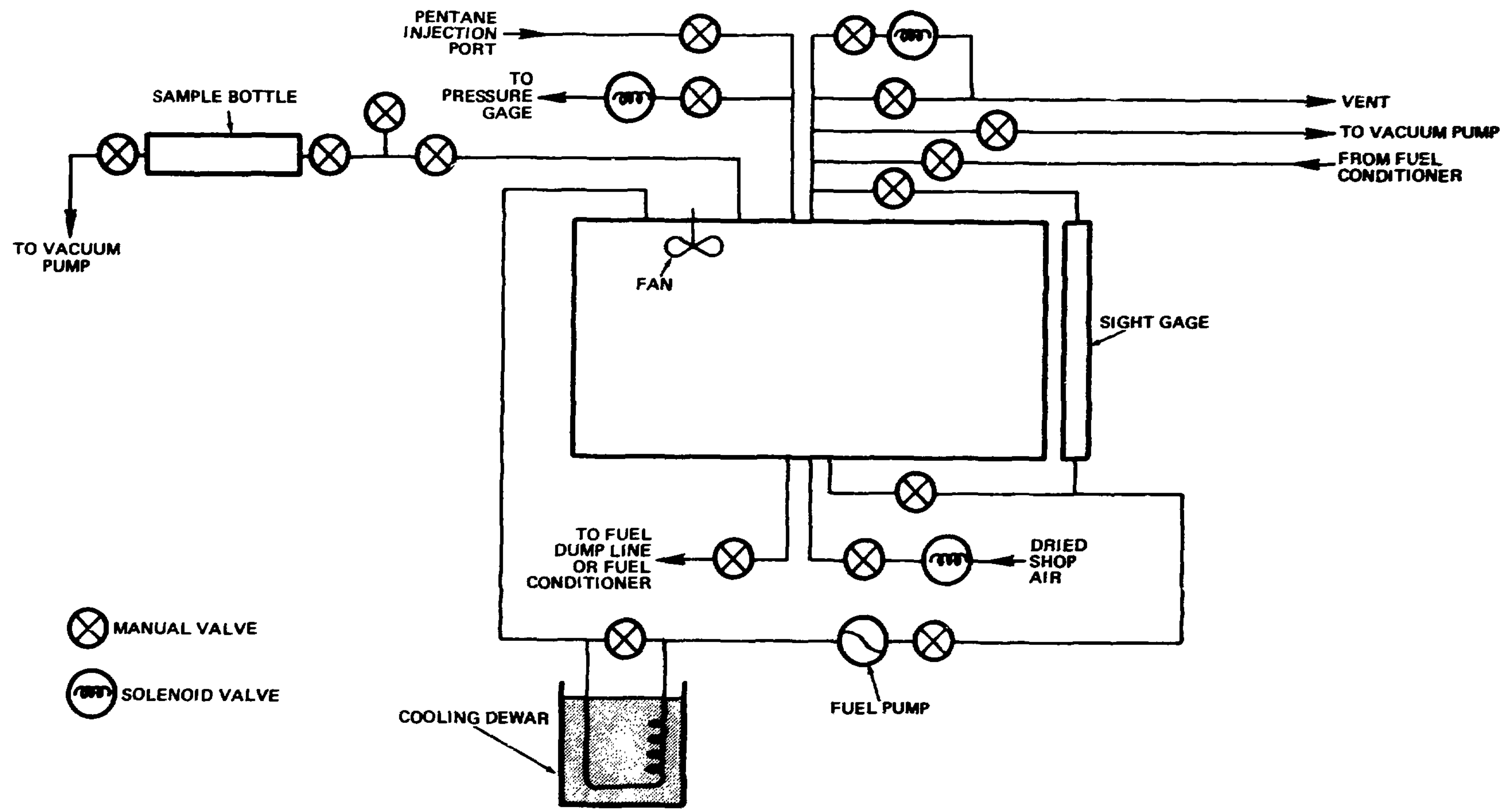


FIGURE 18. COMBUSTION COMPARISON TEST SETUP.

pressure transducer. The fuel circulation line was for the purpose of increasing the rate of evaporation of the JP-4. The fuel was sprayed directly onto the rotating fan blades. In order to remove the heat added to the fuel by the fuel circulation pump, and in order to provide additional fuel temperature control, the fuel was circulated through a dewar filled with a mixture of water, antifreeze, and dry ice. The JP-4 was cooled in a fuel conditioning system and circulated through the conditioning system and the test article in order to bring the test article to the desired temperature. A gas chromatographic analysis of a sample of the liquid fuel is shown in Appendix II. Each pentane test required about 45 minutes to perform, while each JP-4 test required about six hours.

TEST PROCEDURE

Since the procedure for the performance of the pentane tests was different from that of the JP-4 tests, the procedures are shown separately.

Pentane Test Procedure

1. Evacuate test tank to less than 0.5 psia.
2. Draw the desired quantity of liquid pentane from a calibrated burette and into the test tank.
3. Turn on fan.
4. Pressurize test article with dry shop air to 16.5 psia.
5. Wait a few minutes and draw a sample into the sample bottle.
6. Ignite the mixture in the sample bottle and record the pressure versus time data.
7. Repeat sampling and ignition procedure until the samples produce nearly identical results. This usually occurred with the first two samples taken.
8. Bleed the test tank pressure down to 16.2 psia through the solenoid operated vent valve.
9. Close all valves, ignite the mixture in the tank, and record the test data.
10. Open the vent and purge the tank with the dry shop air for at least ten minutes.

JP-4 Test Procedure

1. Condition approximately 120 gallons of JP-4 fuel to below the desired test temperature in the refrigeration section of the fuel conditioning system.
2. Fill the test tank with the JP-4, turn on the fan to stir the liquid, and begin circulation of the fuel through the refrigeration section of the conditioner and the test tank.
3. When the test tank and fuel are at the desired temperature, stop circulation.
4. Slowly withdraw the fuel until approximately two inches of fuel remain in the tank.
5. Begin fuel circulation, spraying the fuel onto the fan and controlling the temperature of the fuel spray.
6. Pressurize the tank with dry shop air to approximately 17.0 psia.
7. Continue to circulate and spray fuel into the tank until all internal tank temperatures are approximately the same (±2°F maximum).
8. Take sample, ignite sample bottle mixture, and record data.
9. Repeat the sampling and ignition procedure until the results are nearly identical.
10. Bleed the test tank pressure down to 16.2 psia through the solenoid operated bleed valve. Stop fuel circulation and turn off the fan.
11. Close all valves, ignite the mixture in the tank, and record the test data.
12. Withdraw the remaining fuel and purge the test tank for at least ten minutes with dry shop air.

The above test procedure for JP-4 introduces a slight error in the JP-4 vapor concentration. At Step 10 the pressure within the tank is reduced from approximately 16.8 psia to 16.2 psia by venting a portion of the ullage gas mixture. This also reduces the partial pressure of fuel vapor in the ullage proportionally. Since the time between this venting and the ignition of the gases (Step 11) is less than two minutes, and since the circulation pump and the fan are turned off, very little evaporation of the liquid fuel to replace this lost fuel vapor can occur. Therefore, the fuel vapor concentration in the ullage is slightly lower than the liquid fuel vapor pressure (i.e., the liquid/vapor system). Since the number of samples to be taken with each test was unknown beforehand and sometimes was as many as seven, it was necessary to pressurize the test tank to above the test pressure of 16.2 psia. This allowed for sufficient sampling without reducing the pressure below 16.2 psia. If additional fuel spraying and mixing were allowed after venting to 16.2 psia, additional sampling would have been required to verify that equilibrium had been obtained, thereby reducing the pressure below 16.2 psia.

The effect of this error on the fuel vapor concentration can be calculated by assuming that the ratio of the fuel vapor partial pressure to the vapor pressure of the fuel at the test temperature is equal to the ratio of the test pressure (16.2 psia) to the pressure before venting (16.6 to 17 psia). This introduces an error of about 3.5% of the fuel vapor concentration. Thus, the actual fuel vapor partial pressure in the tests was about 96.5% of the vapor pressure of the liquid fuel. In converting the liquid fuel temperatures to fuel vapor concentrations via the saturated vapor pressure curve for the particular fuel used, the fuel vapor concentration can be corrected for this error by multiplying the results by .965. This is shown and discussed in the following section.

TEST RESULTS

The results of all of the valid JP-4/pentane combustion comparison tests are shown in Table V. Some of the tests were considered to be invalid due to various technical problems (equipment failures, operator errors, and inability to properly attain desired temperatures) encountered in the performance of these tests. The correct procedures required to attain satisfactory JP-4 fuel vapor/air mixtures evolved as a result of these invalid tests. The temperatures shown for the JP-4 tests on Table V are the average value of the temperatures indicated by each thermocouple in the tank just prior to ignition.

The peak pressure (ΔP) and the times required to attain the peak pressure (Δt_R) are shown as a function of the volume percent of fuel vapor for the pentane tests in Figures 19 and 20. The fuel vapor concentration that will

TABLE V

JP-4/PENTANE COMBUSTION COMPARISON TESTS – PENTANE TESTS

TEST NO.	VOLUME PERCENT PENTANE	TEST PRESSURE (psia)	PEAK PRESSURE (ΔP) (psi)	TIME TO PEAK (Δt) PRESSURE (sec)
13	2.5	16.20	112	320
14	2.5	16.20	111	332
15	3.0	16.20	120	255
16	3.0	16.20	126	230
17	3.5	16.19	120	155
18	3.5	16.20	123	180
19	3.9	16.13	118	195
20	4.0	16.20	117	212
21	4.5	16.19	105	584
22	4.6	16.20	98	783
23	5.0	16.21	87	1480
24	5.0	16.20	83	1650
27	5.5	16.20	8	316
28	5.5	16.20	9	315
29	2.0	16.20	93	590
30	2.0	16.20	93	530
31	1.5	16.20	—	—
32	1.5	16.06	—	—
33	1.5	16.20	—	—
34	6.0	16.20	3	1240

TABLE V (continued)

JP-4/PENTANE COMBUSTION COMPARISON TESTS – PENTANE TESTS				
TEST NO.	VOLUME PERCENT PENTANE	TEST PRESSURE (psia)	PEAK PRESSURE (ΔP) (psi)	TIME TO PEAK (Δt) PRESSURE (sec)
35	6.0	16.20	3	1780
36	6.0	16.20	3	1300
37	6.5	16.19	1	650
38	6.5	16.19	—	—
39	6.5	16.20	1	1350
40	4.0	16.19	117	240
41	7.1	16.20	—	—

TABLE V (continued)

JP-4/PENT[illegible] COMBUSTION COMPARISON TESTS – JP-4 TESTS				
TEST NO.	TEMPERATURE	TEST PRESSURE (psia)	PEAK PRESSURE (ΔP) (psi)	TIME TO PEAK (Δt) PRESSURE (sec)
49	26	16,13	123	,210
51	22	16.18	127	.310
52	23	16.20	125	.250
55	44.5	16.18	78	2.20
56	24.5	16.16	126	.230
57	23	16.20	118	.250
60	42	16.19	86	1.56
61	48	16.20	72	2.06
62	37	16.21	87	.360
63	39	16.20	90	.580
64	36	16.16	103	.300
66	33	16.20	105	.310
67	12	16.20	126	.320
68	13	16.20	127	.300
70	17.5	16.20	124	.210

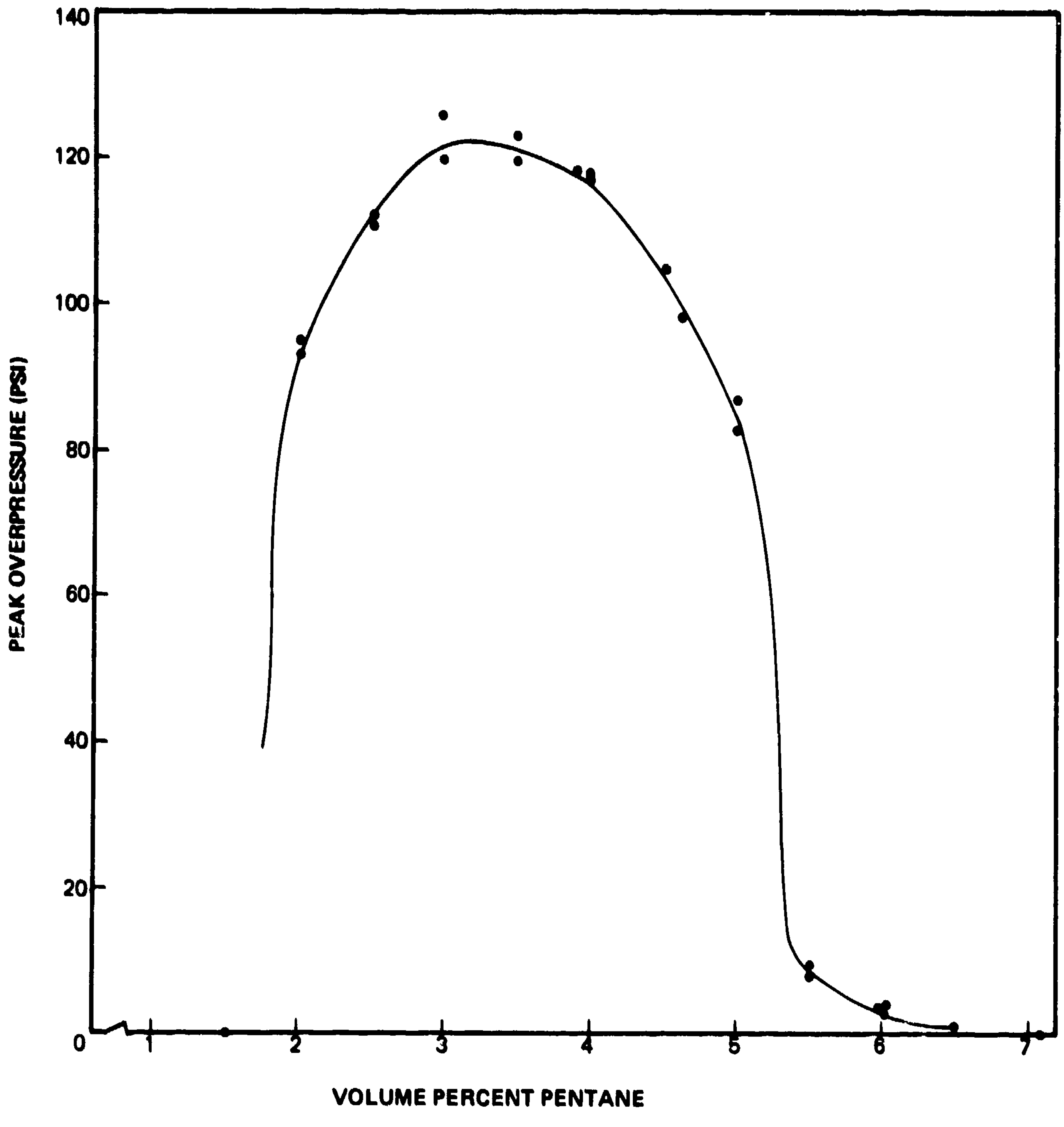


FIGURE 19. PEAK OVERPRESSURE VS VOLUME PERCENT PENTANE.

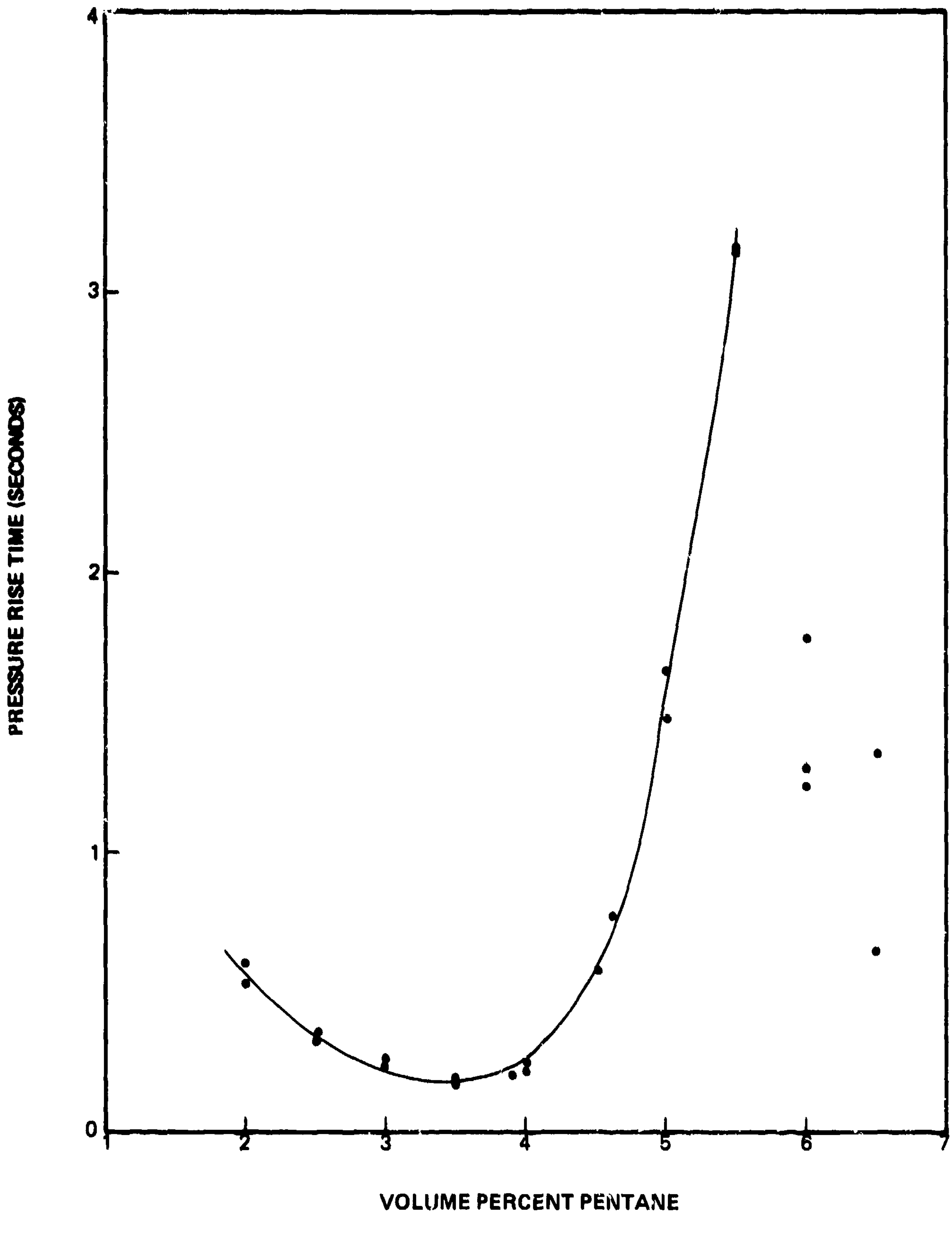


FIGURE 20. PRESSURE RISE TIME VS VOLUME PERCENT PENTANE.

completely react with all the available oxygen in the air (i.e., no excess fuel or air) is referred to as stoichiometric. The stoichiometric fuel vapor concentration for pentane is 2.56% by volume. Figures 19 and 20 demonstrate that the fastest reactions (lowest Δt_R) and the highest peak combustion overpressures (ΔP) occur slightly to the rich side of stoichiometric for pentane. This is not unusual, and most other fuels behave similarly. Also, the minimum spark ignition energy required to ignite a mixture and the greatest flame speed for most fuel vapor/air mixture occurs to the rich side of stoichiometric.

Based upon the data presented in Figures 19 and 20, it can be concluded that the pentane vapors could not be entirely ignited if the pentane vapor concentration exceeded 5.5%. Although some pressure rises did occur above 5.5%, these are considered to be the result of local burning in the vicinity of the spark ignition source. Mixtures that are richer than stoichiometric exhibit slower flame speeds; therefore, any reactions which occur in richer mixtures would be expected to require much longer to attain the peak combustion overpressure Figure 20 demonstrates this phenomena. The fact that the reactions at 6 and 6.5% pentane exhibit lower times to peak pressure than the mixtures at 5.5% pentane indicates that these richer reactions were incomplete. These pentane/air mixtures should have been flammable up to 7.8% pentane by volume.[9] However, the spark plug was recessed about three inches from the inner surface of the test tank wall in a horizontal pipe having an inside diameter of about 1.5 inches. A flame requires a minimum tube diameter (quenching distance) in order to propagate through a tube. For the richer pentane/air mixtures, this quenching distance exceeds 1.5 inches, thereby preventing flame propagation into the test tank. Also, flammability limits vary considerably, depending on the direction of flame propagation. For example, the rich flammability limit for pentane varies from about 4.6 to 8.0% as the direction of flame propagation is varied from downward to horizontal to upward.[9] The tests performed with JP-4 vapors utilized the same ignition source, thereby allowing a comparison of the two fuels independent of the ignition source.

The results of the JP-4 tests are shown in Figures 21 and 22. Before the results of these tests can be compared with Figures 19 and 20, it is necessary

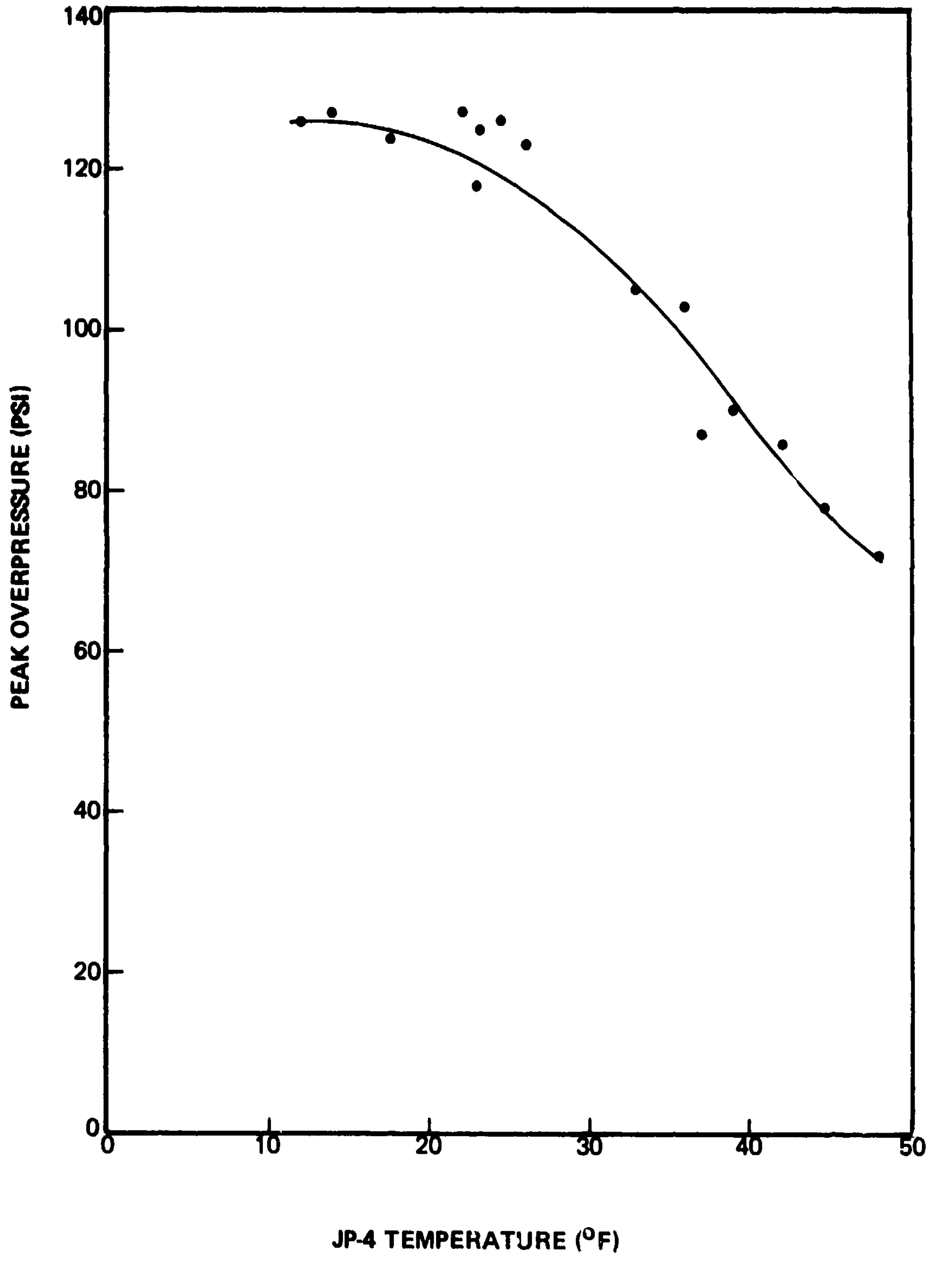


FIGURE 21. PEAK OVERPRESSURE VS JP-4 TEMPERATURE.

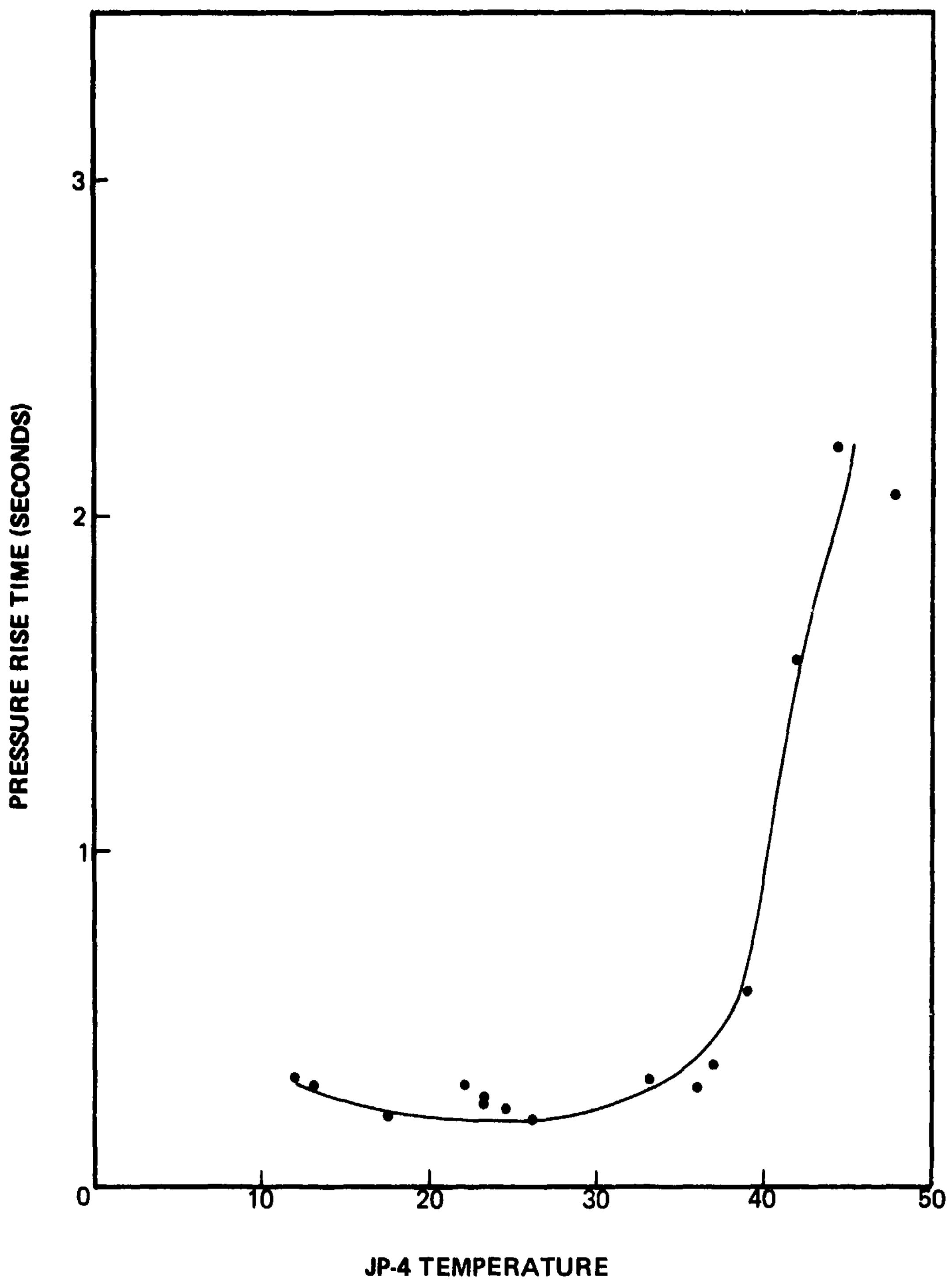


FIGURE 22. PRESSURE RISE TIME VS JP-4 TEMPERATURE.

to convert the liquid JP-4 fuel temperature to volume percent fuel vapor. This conversion requires the use of the fuel vapor pressure versus temperature relationship. Seventeen different samples of the JP-4 fuel used in these tests were submitted to the Fuels Branch of the Aero Propulsion Laboratory for vapor pressure analysis. The vapor pressure of these samples varied from 2.3 to 2.6 psi at 100°F with an average value of 2.41 psia. Based upon the results of these vapor pressure analyses, the saturated fuel vapor concentration versus temperature relationship shown in Figure 23 was constructed. Figure 23 presents the fuel vapor concentration that would exist in the ullage of a fuel tank pressurized to 16.2 psia, containing the JP-4 fuel used in these tests, and under equilibrium (saturated) conditions. The JP-4 fuel vapor concentration in these JP-4 tests can be obtained by converting the temperature values on the abscissas of Figures 21 and 22 to fuel vapor concentration via Figure 23. The procedure used in these tests introduces an error of about 3.5% of the fuel vapor concentration, as discussed in the previous section. Consequently, the fuel vapor concentrations must be corrected by multiplying the fuel vapor volume percent by .965. When this conversion and the correction are applied, the results are as shown in Figures 24 and 25. In order to compare these results with those of pentane, the data shown in Figures 19 and 20 have been included in Figures 24 and 25.

Figures 24 and 25 demonstrate a surprising difference between the JP-4 tests and the pentane tests. The curves for JP-4 appear to lie about one percent to the left of the curves for pentane. The JP-4 vapor acts as if it were a fuel having a molecular weight that is greater than pentane and nearer to heptane. This is somewhat surprising and may not be representative of JP-4 fuel in general. The quantities of various constituents of JP-4 can vary over a wide range. A recent survey of the properties of JP-4 fuel[25] demonstrates these variations. Also, the JP-4 fuel used in these tests has a vapor pressure that is lower than the average. A higher vapor pressure JP-4 will have a greater concentration of the lighter hydrocarbons and would be expected to more closely simulate the combustion characteristics of pentane. More extensive testing and analysis is required before the effects of varying quantities of the constituents of JP-4 fuel vapors on their combustion is known.

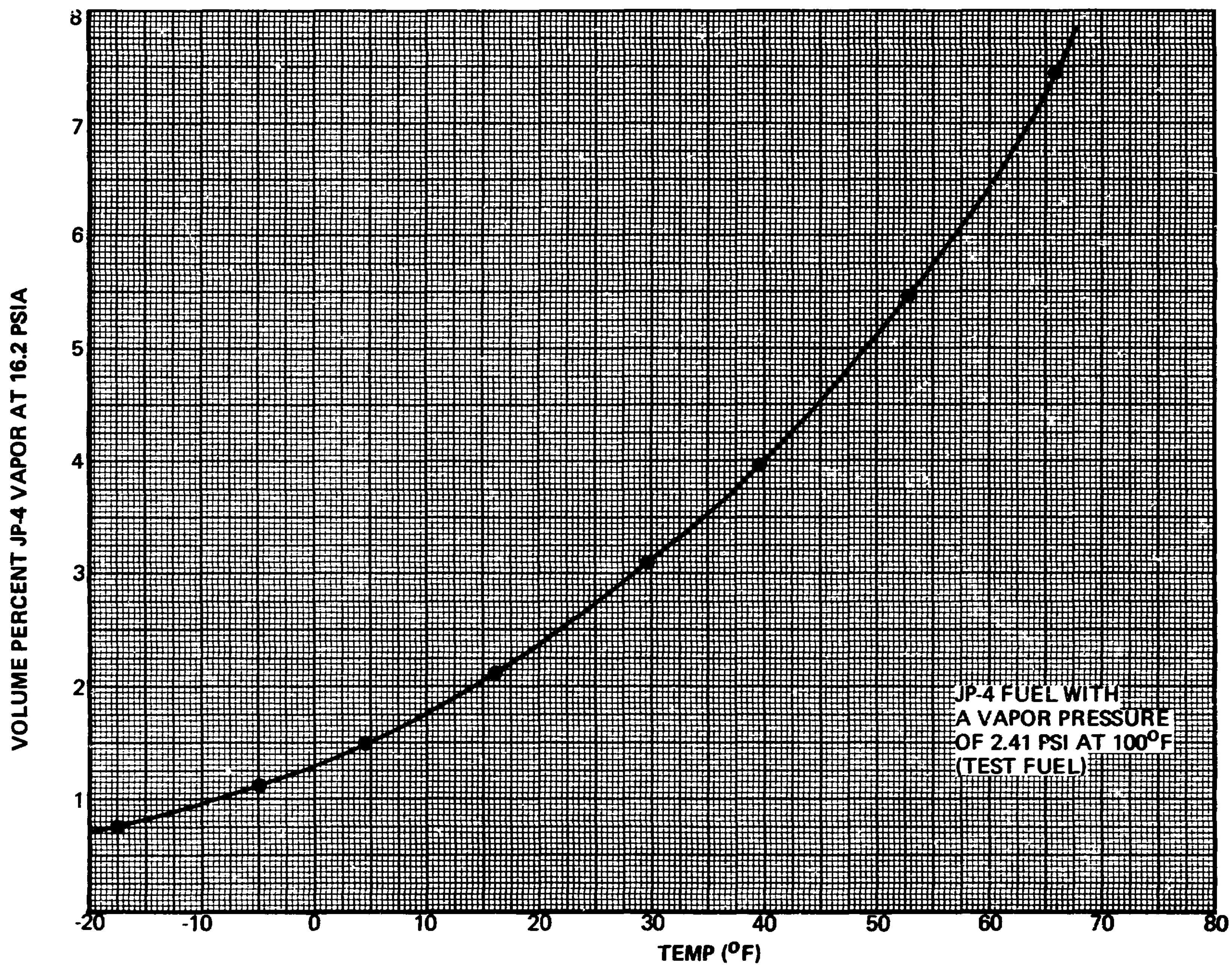


FIGURE 23. JP-4 VAPOR CONCENTRATION VS FUEL TEMPERATURE

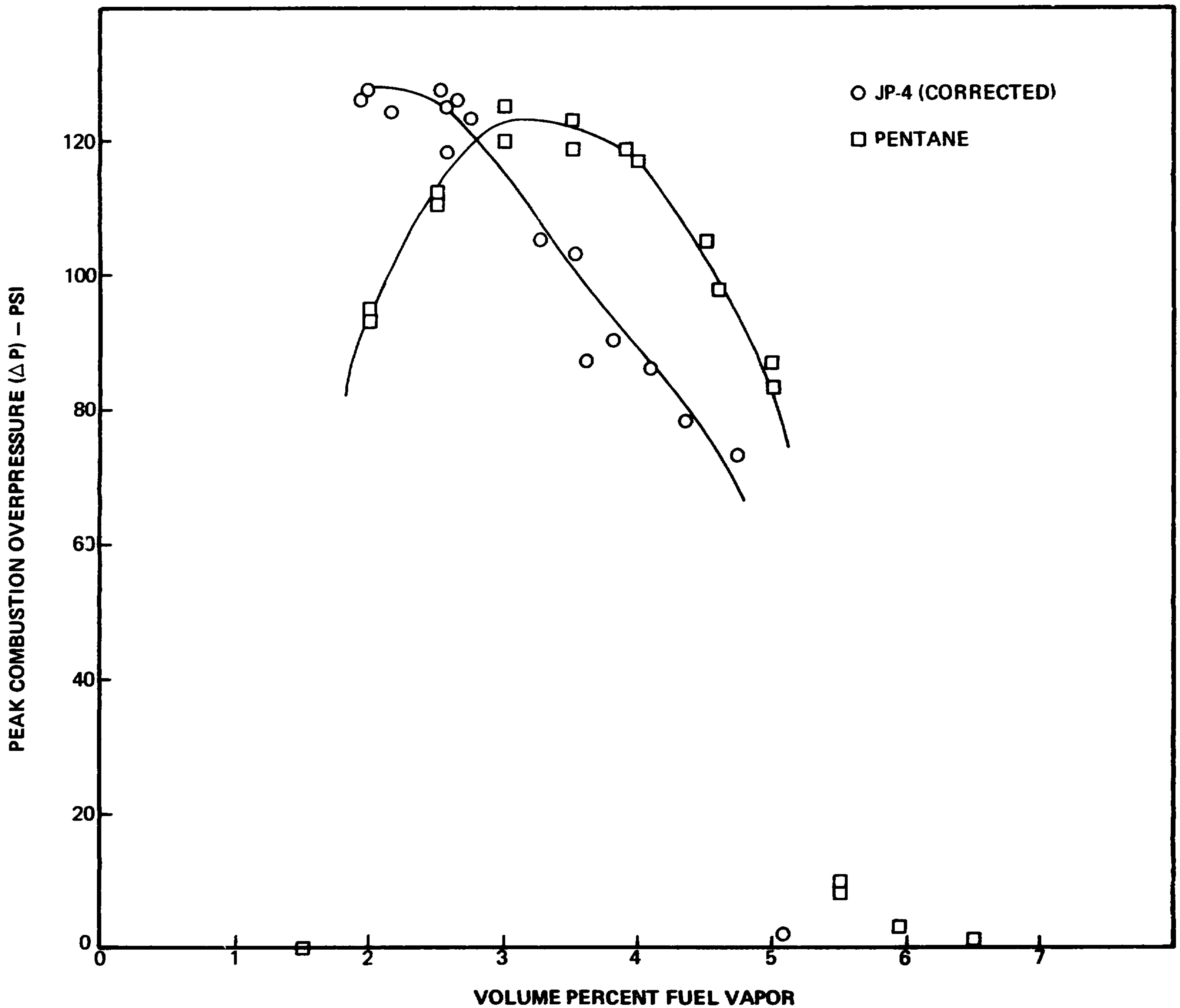


FIGURE 24. PRESSURE RISE VS PERCENT FUEL VAPOR.

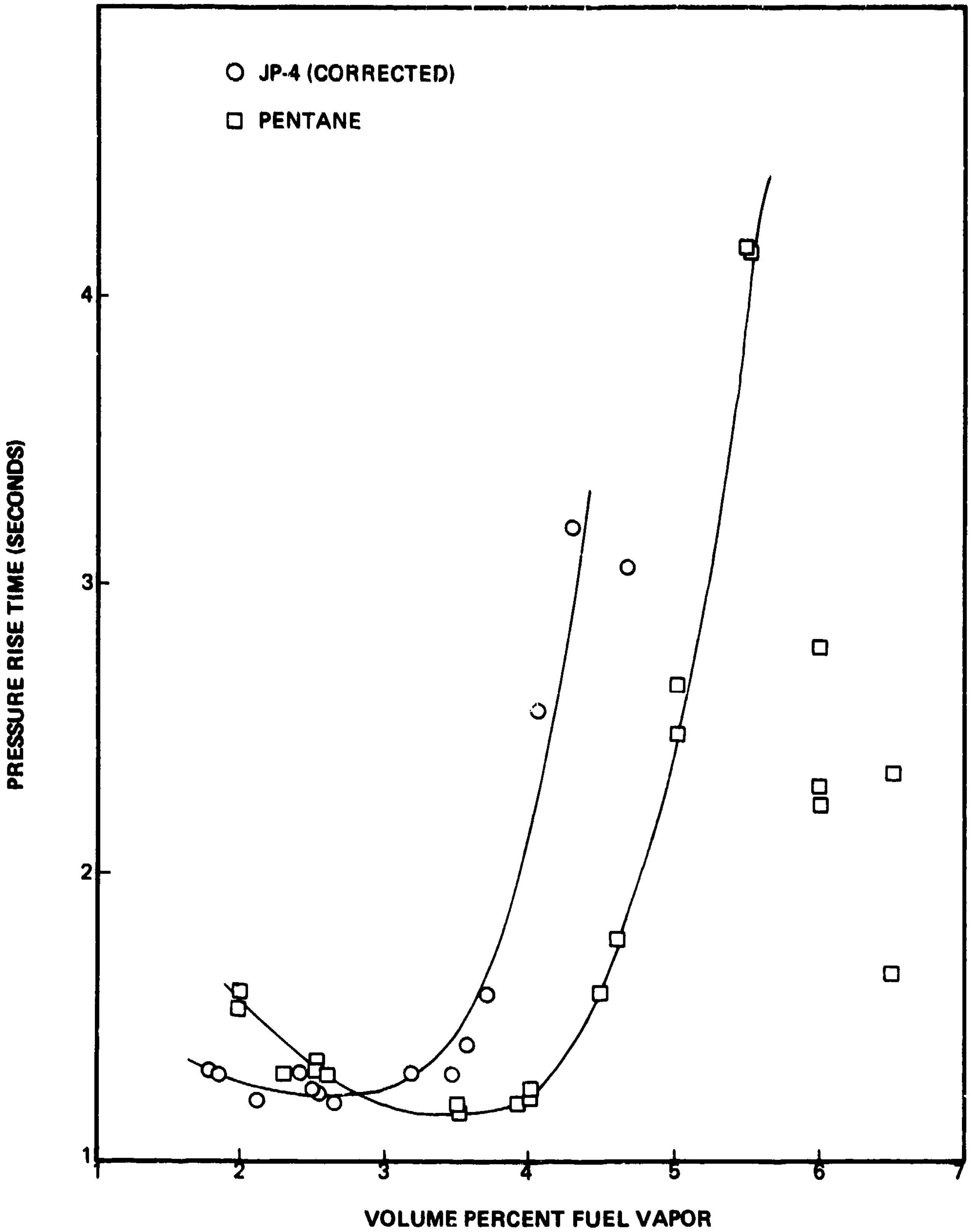


FIGURE 25. PRESSURE RISE TIME VS PERCENT FUEL VAPOR.

The maximum combustion overpressure and the time required to attain this overpressure are comparable for both the pentane and JP-4 tests. Both of these properties are functions of the test tank geometry and test conditions, and the results can be expected to vary to some extent for different test tanks and test conditions. Thus, although specific fuel vapor concentrations of pentane and JP-4 vapors may not produce identical results when ignited, a worst case fuel vapor concentration of either of the two fuels will produce nearly identical combustion overpressures and overpressure rise times.

CONCLUSIONS

Based upon the data available in the literature (e.g., Table IV) pentane appears to be a reasonable fuel to substitute for JP-4 in any test program requiring well controlled fuel vapor concentrations. However, based upon the testing described in this section, a correction to the data obtained with pentane seems in order. Thus, for the purpose of extrapolating the results of the uninerted ullage tests (Figures 7, 8, 9, 10) to the JP-4 fuel used in these combustion comparison tests, the following relationship may be applied.

Volume percent JP-4 vapor = Volume percent pentane vapor - 1%

This is at best an oversimplified relationship which may not apply to different samples of JP-4 fuel and will not apply to fuel vapor concentrations less than stoichiometric. Although pentane was used in the inerted ullage tests, the purpose of these inerted tests was to evaluate the 10% oxygen concentration at a worst case fuel vapor concentration. Since the worst case fuel vapor concentrations for these two fuels should produce similar results, no change in the inerted ullage test data or results is required.

It is recommended that a neat hydrocarbon fuel (e.g., pentane, propane, or hexane) be used to simulate JP-4 vapors in any tests requiring well controlled and accurate fuel vapor concentrations. This may result in a problem when a direct comparison or correlation between the neat hydrocarbon fuel concentration and the same concentration of JP-4 vapors is required, or when other properties (e.g., the autoignition temperature) are of great importance and differ significantly between the two fuels.

Section VI

CONCLUSIONS AND RECOMMENDATIONS

VOID AREA TESTS

The results of the void area tests are shown in Figure 5, which is a plot of the probability of a void area fire (P_f) versus fragment velocity. These results apply only to the conditions tested, and extrapolation to different conditions may produce considerable error. Some of these different conditions and the manner in which they may affect P_f are discussed in Section II. As demonstrated by Figure 5, there appears to be no significant difference between the results obtained with the 0.090 in. 2024-T3 aluminum striker plates and the 0.060 in. 6Al-4V striker plates. At about 2,000 ft/sec the probability of a fire rapidly increases from zero to one. Also, 16 tests were performed with no striker plate and a 0.060 in. 6Al-4V titanium entrance plate, simulating an integral fuel tank (no void area). These few tests indicate that P_f is much lower for this test configuration than for the other two configurations tested.

UNINERTED ULLAGE TESTS

The effects of the fuel/air ratio, fragment velocity, fragment size, and entrance plate material (simulated tank wall) on the probability of a fuel tank explosion (P_e) are shown in Figures 7 through 10. These figures demonstrate the following:

- The fuel/air ratio has the greatest effect on P_e.
- The 0.060 in. 6Al-4V titanium entrance plates resulted in higher values of P_e than the aluminum entrance plates.
- P_e generally increases with increasing fragment velocity.
- The 180 grain and 90 grain hexagonal fragments produced similar values of P_e at the same velocities. Note that the low velocities for the two fragments were different.
- The peak combustion overpressures varied from approximately 120 psi to 40 psi as the pentane concentration was increased from the near stoichiometric value until ignition no longer occurred.

- The few tests performed to compare the diamond shaped fragment to the hexagonal fragment of the same weight indicate that the diamond shaped fragment may be less of a threat than the hexagonal fragment. The difference observed in the testing is small and the comparison was made only with the high velocity and the aluminum entrance plate test condition.

The tests performed to evaluate the effect of the entrance plate thickness and paint on the entrance plate are discussed in Section III along with the potential effects of certain untested variables.

Due to the need to accurately control the fuel vapor concentration in these uninerted ullage tests, and due to rapid turnaround time required to perform the large number of tests that were necessary, the fuel used in these tests was normal pentane. The combustion comparison tests described in Section V revealed that the pentane vapors did not correlate exactly with JP-4 vapors in terms of the results obtained at the same fuel vapor concentrations. Therefore, it is necessary to apply a correction to the data presented in Figures 7 through 10. This correction has been applied and the four corrected graphs have been redrawn and are presented in Figures 26 through 29.

INERTED ULLAGE TESTS

As a result of the testing performed in this program and that reported in References 1 and 20, it can be concluded that the level of nitrogen inerting (10% oxygen by volume) proposed for fuel tanks will effectively prevent significant combustion overpressures from occurring in most instances. The limited conditions under which significant overpressures can occur are discussed in Section IV. The results of these inerted ullage tests do correlate with those of Reference 1 and provide a very crude method for approximating the effect of the fuel tank ullage volume on the peak combustion overpressure occurring in a 10% oxygen mixture under worst case conditions. The very significant effect of pressure relief through projectile entrance and exit holes was also verified by these tests. Finally, these tests verified that a flame could not propagate through a 10% oxygen/pentane/nitrogen gas mixture.

SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	180 GR. HEX	5750 FPS	.060 6AL-4V TITANIUM
▲	180 GR. HEX	3750 FPS	.060 6AL-4V TITANIUM
■	180 GR. HEX	5750 FPS	.200 6AL-4V TITANIUM
□	180 GR. HEX	5750 FPS	.060 6AL-4V TITANIUM (PAINTED)

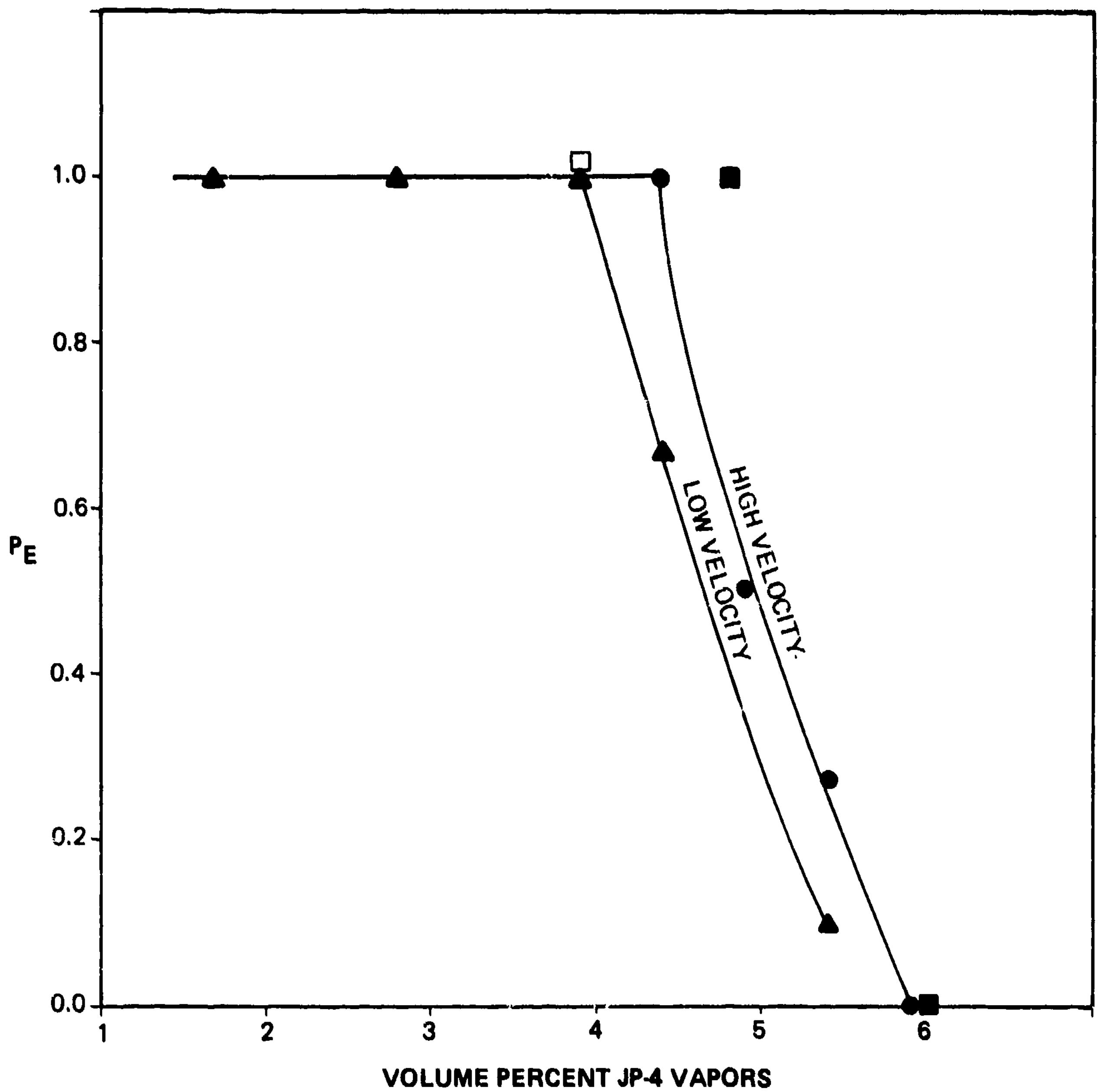
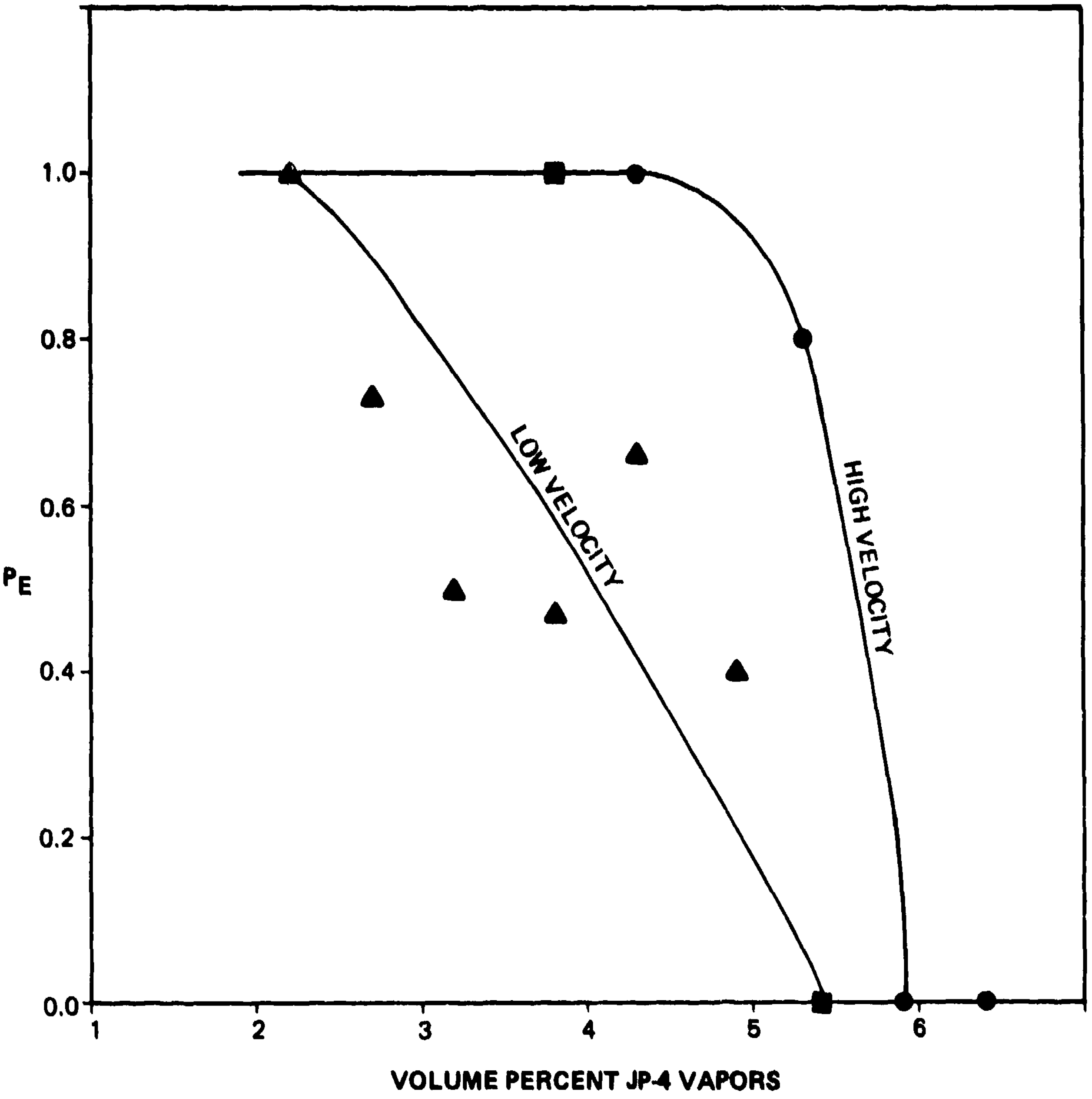
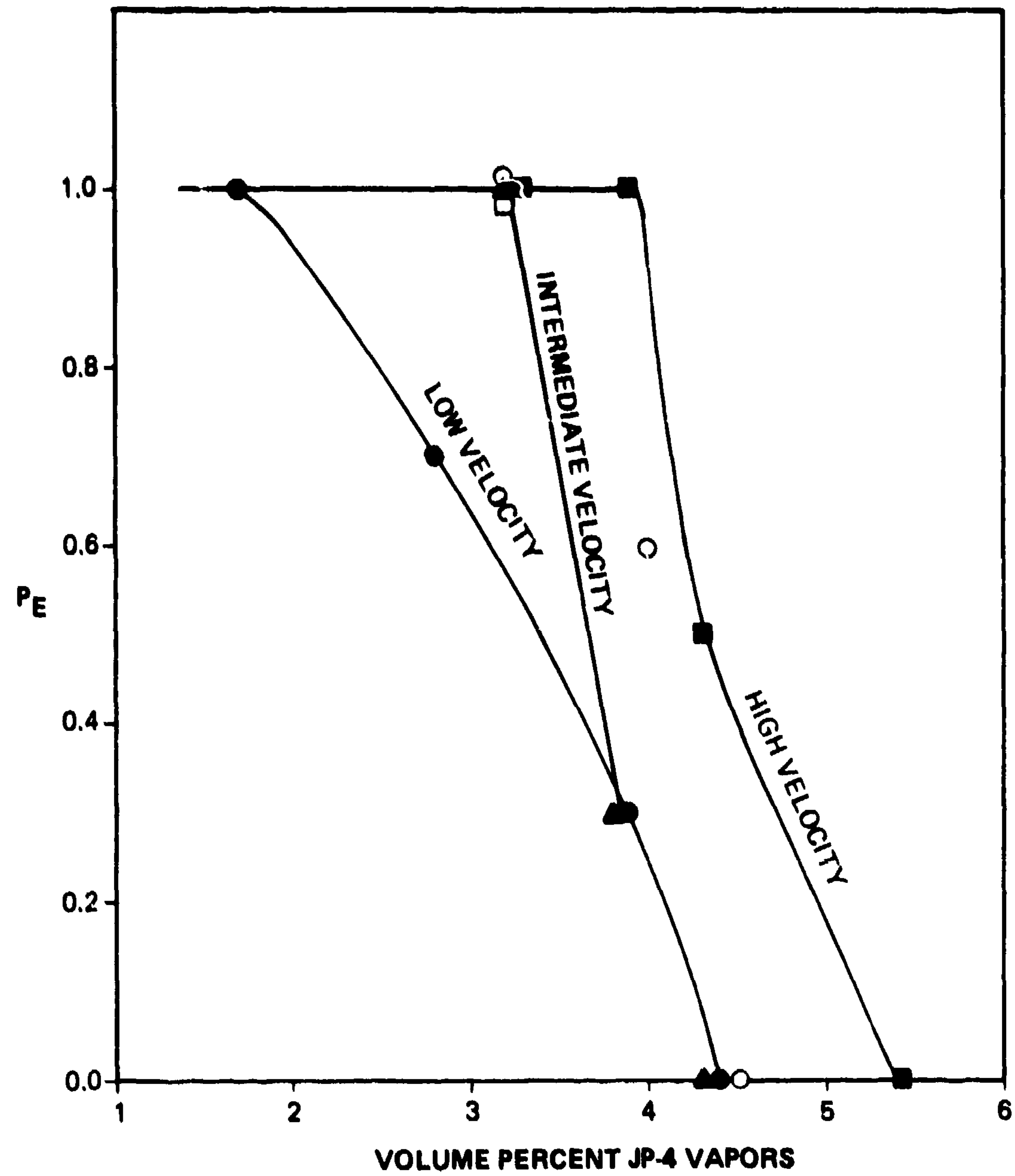


FIGURE 26. PROBABILITY OF EXPLOSION VS PERCENT JP-4 VAPORS.



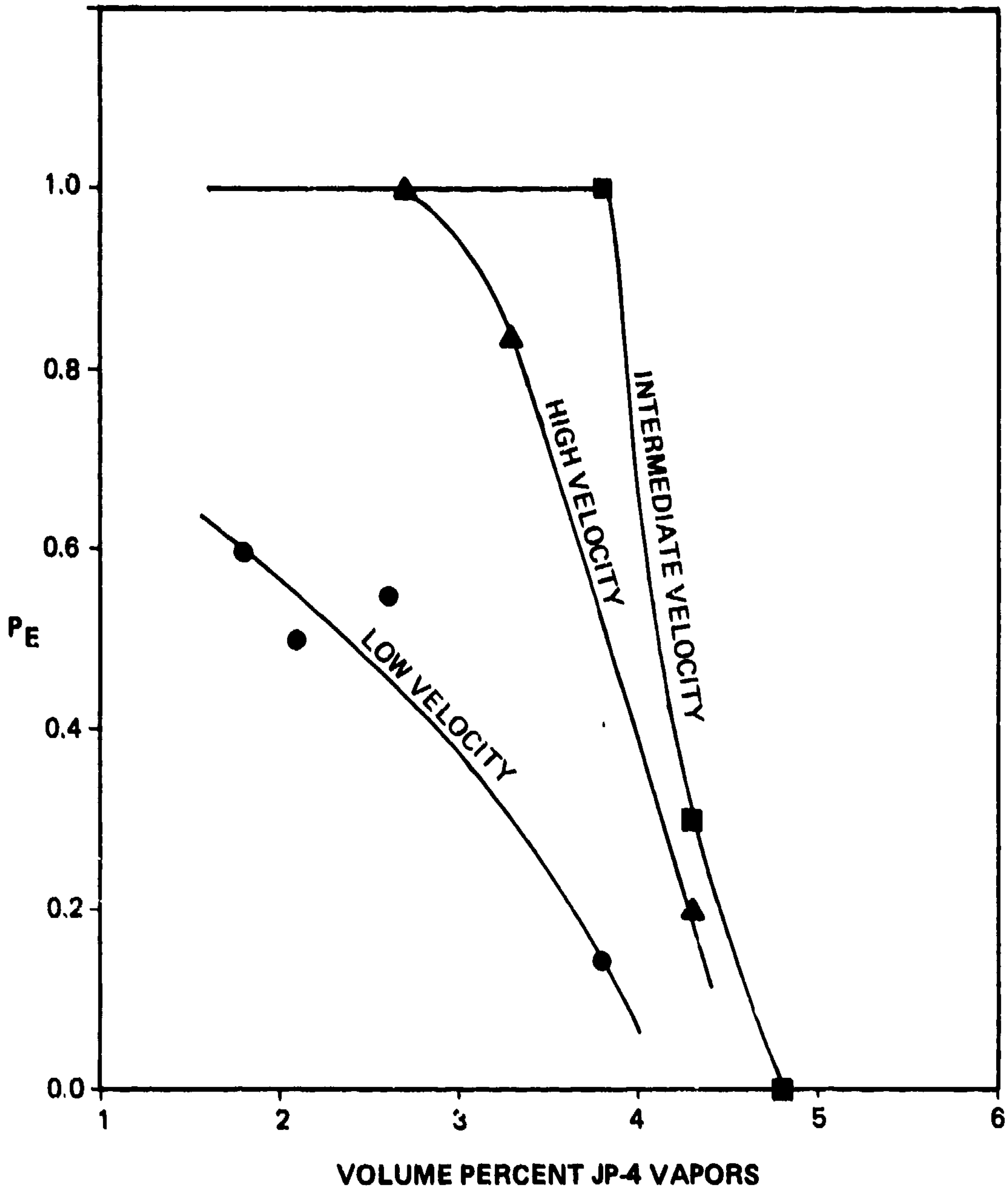
SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	90 GR. HEX	5750 FPS	.060 6AL-4V Ti
▲	90 GR. HEX	2750 FPS	.060 6AL-4V Ti
■	90 GR. HEX	4750 FPS	.060 6AL-4V Ti

FIGURE 27. PROBABILITY OF EXPLOSION VS PERCENT JP-4 VAPORS.



SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	180 GR. HEX	3750 FPS	.090 2024-T3 AL
▲	180 GR. HEX	4750 FPS	.090 2024-T3 AL
■	180 GR. HEX	5750 FPS	.090 2024-T3 AL
○	180 GR. DIAMOND	5750 FPS	.090 2024-T3 AL
□	180 GR. DIAMOND	5750 FPS	.090 2024 T3 AL PAINTED

FIGURE 28. PROBABILITY OF EXPLOSION VS PERCENT JP-4 VAPORS.



SYMBOL	FRAG	VELOCITY	ENTRANCE PLATE
●	90 GR. HEX	2750 FPS	.090 2024-T3 AL
▲	90 GR. HEX	5750 FPS	.090 2024-T3 AL
■	90 GR. HEX	4750 FPS	.090 2024-T3 AL

FIGURE 29. PROBABILITY OF EXPLOSION VS PERCENT JP-4 VAPORS.

Appendix I

CALCULATION OF THE QUANTITY OF LIQUID PENTANE REQUIRED TO PRODUCE A GIVEN PARTIAL PRESSURE OF PENTANE VAPOR AFTER EVAPORATION

From ideal gas laws,

$$PV = nRT$$

where

P = the desired partial pressure of pentane

V = volume of the test article

n = number of moles of pentane required

R = gas constant

T = test tank temperature (degrees Rankine)

from this,

$$n = \frac{PV}{RT}$$

or

$$m = \frac{PVM}{RT}$$

where

m = mass of pentane liquid required

M = molecular weight of pentane = 72.15

furthermore,

$$m = V_L \rho$$

where

V_L = volume of liquid pentane required

ρ = density of liquid pentane

substituting,

$$V_L = \frac{PVM}{\rho RT}$$

also,

$$P = (\%\ C_5H_{12})\ P_T$$

where

$(\%\ C_5H_{12})$ = volume percent of pentane vapors desired

P_T = total pressure after mixing

thus,

$$V_L = \frac{(\% C_5H_{12})\ P_T\ VM}{\rho RT}$$

Appendix II

COMPONENTS OF JP-4

Mass (%)	Hydrocarbon	Mass (%)	Hydrocarbon
0.01	2-Methylpropane (isobutane)	3.94	n-Nonane*
0.09	n-Butane	0.48	
0.42	2,2-Dimethylpropane (neopentane)	0.16	
		0.76	
1.31	2-Methylbutane (isopentane)	1.40	
		0.50	
1.50	n-Pentane*	3.49	
0.15	2,2-Dimethylbutane	0.68	
0.32	2,3-Dimethylbutane	1.34	
2.65	2-Methylpentane	4.59	n-Decane*
1.07	3-Methylpentane	1.23	
2.57	n-Hexane*	0.46	
1.40	2,2-Dimethylpentane	0.94	
0.12		0.36	
1.08	3,3-Dimethylpentane	0.06	
3.10	2-Methylhexane	0.21	
3.27	2,3-Dimethylpentane	2.33	n-Hendecane*
2.26	3-Methylhexane	0.35	
7.04	n-Heptane*	0.23	
3.15	(Methylcyclohexane or isooctane)	0.48	
		0.82	
1.64	2,2,3-Trimethylpentane	0.20	
0.49		2.38	n-Dodecane*
0.28		0.84	
5.78	2-Methylheptane	0.59	
4.21	3-Methylheptane	0.40	
1.57		0.69	
0.66		1.59	n-Tridecane*
6.48	n-Octane*	0.11	
0.10		0.21	
0.28		0.22	
0.67		0.40	
1.78		0.06	
0.95		0.20	
0.13		0.97	n-Tetradecane*
1.24	Xylene or Nonane Isomer	0.04	
4.04		0.17	
2.29		0.33	n-Pentadecane*
0.30			
1.33			

*Normal Alkane

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